Thesis/
Reports
Andersen,
W. H.

DYNAMIC INTERACTION OF FIRE RETARDANT DROPLETS WITH FUEL, AND CORRELATION WITH THE RHEOLOGICAL PROPERTIES OF THE RETARDANT

Final Report

to

UNITED STATES DEPARTMENT OF AGRICULTURE

FOREST SERVICE

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION

A report of research performed under the auspices of the Intermountain Forest and Range Experiment Station, Ogden, Utah.

Property of
National FS Library
USDA Forest Service
240 W Prospect Rd
Fort Collins CO 80526

Shock Hydrodynamics
A DIVISION OF Whittaker

DYNAMIC INTERACTION OF FIRE RETARDANT DROPLETS WITH FUEL, AND CORRELATION WITH THE RHEOLOGICAL PROPERTIES OF THE RETARDANT

FINAL REPORT
(7660-02)

W. H. Andersen
Jan Y. Wong

Contract 839-2031-76

Period Covered: 28 June 1976 Through 31 July 1978

29 September 1978

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
USDA Forest Service
Ogden, Utah 84401

The research conducted under this contract is a part of a program to improve fire control technology, specifically through the use of fire retardant chemicals and delivery systems whose chemical and/or design characteristics are tailored to fuel and fire situation needs. This program is being conducted at the Northern Forest Fire Laboratory. Information or questions regarding these studies should be directed to the:

Northern Forest Fire Laboratory
Drawer G
Missoula, Montana 59801

SHOCK HYDRODYNAMICS DIVISION
WHITTAKER CORPORATION
4716 Vineland Avenue
North Hollywood, California 91602

ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance and helpful discussions given to this program by Dr. L. Zernow and Mr. J. A. Burchfield of Shock Hydrodynamics, and Mr. Charles W. George, the Contract Monitor of the Forest Service. The excellent work of the draftsman, Mr. Gene Allen, in the inking of the many difficult figures and preparation of the photographs is also much appreciated.

TABLE OF CONTENTS

		Page
	SUMMARY	vii
1.	INTRODUCTION	1
	1.1 Scope of the Present Program	2
2.	BACKGROUND AND NATURE OF THE PROBLEM	2
	2.1 Droplet Sizes of Aerially-Dispersed Retardants	2
	2.1.1 Effect of the Physical and Rheological Properties of the Fluid	3
	2.1.2 Relation to Fuel Wetting by the Retardant	4
	2.2 Fuel Wetting by a Dispersed Retardant	4
	2.2.1 Liquid Storage on Fuel	5
	2.2.2 Effect of the Physical and Rheological Properties of the Fluid	6
3.	BEHAVIOR OF A LIQUID DROP IMPACTING WITH A DOWEL	9
	3.1 General Approach	9
	3.2 Experimental Setup and Procedures	10
	3.2.1 Dowel Weighing	10
	3.2.2 Splatter Pattern Observations	14
	3.2.3 High Speed Photography	14
	3.2.4 Fire Retardant Preparation	15
	3.2.5 Liquid Drop Preparation	15
	3.2.6 Prewetting Procedure	16
	3.2.7 Dowel Impact Angle	16
	3.2.8 Off-Center Impact	16
	3.3 Experimental Results and Discussion	16
	3.3.1 Liquid Retention on Dry Dowels After Normal Incidence Drop Impaction	16
	3.3.2 Effect of Dowel Impact Angle	23
	3.3.3 Effect of Prewetting the Dowel	24
	3.3.4 Liquid Spread Area on the Dowels	26
	3.3.5 High Speed Photographic Studies	28
	3.3.6 Discussion of the Splatter Patterns	45
	3.3.7 Drop Evaporation During Free Fall	52
4.	RETARDANT WETTING OF SIMULATED FUEL STRUCTURES	54
	4.1 Fuel Structure Design and Experimental Procedure	54
	4.1.1 Experimental Procedure	54

TABLE OF CONTENTS (con't.)

4.2 Wetting Characteristics of the Birch Dowel Tree 56

4.2.1 Liquid Recovery and Splatter 56
4.2.2 General Observations 58
4.2.3 Efficiency of Liquid Retention 63
4.2.4 Average Film Thickness 64
4.2.5 Effect of Drop Size 66
4.2.6 Effect of Extending the Tree Height 66
4.2.7 Measurement of Liquid Retention by Dowel Immersion 71

4.3 Wetting Characteristics of the Polyethylene Dowel Tree . 74

4.3.1 General Wetting Behavior and Liquid Recovery . . . 74
4.3.2 Liquid Retention and Film Thickened 75
4.3.3 Effect of Surface Roughness 77

5. RETARDANT WETTING OF REAL FUEL STRUCTURES 82

5.1 Wetting Characteristics of Twigs with Bark 82

5.1.1 General Wetting Behavior and Liquid Recovery . . . 82
5.1.2 Liquid Retention and Film Thickness 84

5.2 Wetting Characteristics of a Structure with Waxy Leaves . 84

5.2.1 General Wetting Behavior and Liquid Recovery . . . 87
5.2.2 Liquid Retention and Film Thickness 87
5.2.3 Effect of Drop Size 87

5.3 Wetting Characteristics of a Structure with Needles . . . 92

5.3.1 General Wetting Behavior 92
5.3.2 Liquid Recovery and Retention on the Structure . . 95

5.4 Wetting Characteristics of a Small Real Fuel Structure. . 95

5.4.1 Wetting Behavior, Liquid Recovery and Tree Retention 95
5.4.2 Relative Film Thickness 98

6. FURTHER DISCUSSION AND ANALYSIS 103

6.1 On The Development of a Wetting Model 103

6.1.1 Stratum Fuel Wetting 103

6.1.2 Application and Improvement of the Model 104

6.1.3 Fuel Composition Characterization 105

6.1.4 Additional Wetting Experiments 106

TABLE OF CONTENTS (con't.)

6.1.5 Model Correlations and Data Analysis 106

7. CONCLUSIONS 107

7.1 Summary of Fluid Effects on Fuel Wetting 107

7.1.1 Impact Splatter 107

7.1.2 Liquid Retention on Dowels 108

7.1.3 Tree vs Single Dowel Wetting Behavior 109

7.1.4 Liquid Retention in Real Fuel Structures 110

7.2 Model Development 112

8. RECOMMENDATIONS 112

REFERENCES 113

LIST OF FIGURES

Figure	Title	Page
1a	Experimental Setup for the Dowel Weighing Experiments . .	11
1b	Scale Shield and Mounted Dowel	11
2a	Arbor Balance with Top Shield, Toothpick Stand and Test Dowel	12
2b	Setup for 45° Dowel Impact Test	12
2c	Drop Tower Used for the 42 ft Drop Tests	12
3	Illustration of the Liquid Mass Readings on the Arbor Balance vs Time	13
4	Experimental Setup for Photographing the Impact of a Falling Drop with a Dowel	14
5	Effect of Retardant Rheology, Dowel Size and Composition and Drop Height on the Liquid Retained on a Dry Dowel After Central Impact by a Medium Sized Droplet at Normal Incidence	18
6	Effect of Drop Diameter on the Liquid Retained on a Dry Dowel After Central Impact at Normal Incidence . . .	22
7	Comparison of the Liquid Retention at 0° and 45° Impact Angle	25
8	Comparison of the Liquid Retention on a Dry and Prewet 1/4 Inch Birch Dowel at Normal Incidence	25
9	Dowel Stains Produced on Birch Dowels by Medium Sized Drops	27
10	Spread Area of the Retardants on the Dry Birch Dowels After Impact	28
11	Selected Frames from the Impact of a Falling Drop of Phos-Chek XA with a 1/2 Inch Polyethylene Dowel (42 ft DH)	30
12	Selected Frames from the Impact of a Falling Drop of Phos-Chek XA with a 1/2 Inch Birch Dowel	32
13	Blowups of the Side View Pictures of Figure 12	34
14	Selected Frames from the Impact of a Falling Drop of Fire-Trol 100 with a 1/2 Inch Birch Dowel	36

LIST OF FIGURES (continued)

Figure	Title	Page
15	Selected Frames from the Impact of a Falling Drop of Fire-Trol 931 with a 1/2 Inch Birch Dowel	38
16	Selected Frames from the Impact of a Falling Drop of Fire-Trol 100 with a 1/2 Inch Polyethylene Dowel	40
17	Blowups of the Side View Pictures of Figure 16	41
18	Selected Frames from the Impact of a Falling Drop of Phos-Chek XA with a 1/2 Inch Polyethylene Dowel	42
19	Blowups of the Side View Pictures of Figure 18	43
20	Selected Frames from the Impact of a Falling Drop of Fire-Trol 931 with a 1/2 Inch Polyethylene Dowel	44
21	Selected Frames from the Off-Center Impact of a Falling Drop of Fire-Trol 931 with a 1/2 Inch Polyethylene Dowel	46
22	Selected Frames from the Impact of a Falling Drop of Phos-Chek XA with a 1/2 Inch Birch Dowel at 45°	47
23	Selected Frames from the Impact of a Falling Drop of Phos-Chek XA and Fire-Trol 931 with a 1/2 Inch Polyethylene Dowel at 45°	48
24	Splatter Patterns of Off-Center vs Central Impacts of a Falling Drop of Fire-Trol 931 on a 1/2 Inch PE Dowel	50
25	Splatter Patterns of Off-Center vs Central Impacts of a Falling Drop of Phos-Chek XA on a 1/2 Inch Birch Dowel	50
26	Splatter Patterns of Falling Drops of the Retardants Impacting Centrally with a 1/4 Inch Birch Dowel	51
27	Splatter Patterns of Falling Drops of Retardants Impacting with 1/4 and 1/2 Inch Birch and 1/2 Inch Polyethylene Dowels	51
28	Basic Dowel Tree Structure with Liquid Collecting Pan	55
29	Experimental Retention of the Impacted Liquids (4-5mm Drops) on the Birch Dowel Tree	57
30	Side Splatter Produced by Drops of Liquid Impacting with the Birch Dowel Tree	59
31	Appearance of the Birch Dowel Tree After Dropping Fire-Trol 931 on the Tree	61

Figure	Title	Page
32	Appearance of the Birch Dowel Tree During The Dropping of the Fluids	62
33	Average Film Thickness of the Retained Liquid (4-5 mm Drops) on the Birch Dowel Tree and Its Individual Sections	65
34	Experimental Retention of the Impacted Liquids (Small and Large Drops) on the Birch Dowel Tree and Its Individual Sections	67
35	Average Film Thickness of the Retained Liquid (Small and Large Drops) on the Birch Dowel Tree and Its Individual Sections	68
36	Experimental Retention of the Impacted Liquids on the Extended Birch Dowel Tree, and Its Top Half and Lower Three Sections	70
37	Average Film Thickness of the Retained Liquid on the Extended Birch Dowel Tree, and Its Top Half and Lower Three Sections	72
38	Measured Weight History of the Retardant on the Middle Tree Section	73
39	Experimental Retention of the Impacted Liquids on the Smooth Polyethylene Dowel Tree and Its Individual Sections	76
40	Average Film Thickness of the Retained Liquid on the Smooth Polyethylene Dowel Tree and Its Individual Sections	78
41	Experimental Retention of the Impacted Liquids on the Roughened Polyethylene Dowel Tree and Its Individual Sections	79
42	Average Film Thickness of the Retained Liquid on the Roughened Polyethylene Dowel Tree and Its Individual Sections	81
43	General Appearance of the Green Willow Branch and Rolled Ivy Leaf Dowel Tree	83
44	Experimental Retention of the Impacted Liquids on the Green Willow Dowel Tree	85
45	Approximate Average Film Thickness of the Retained Liquid on the Green Willow Dowel Tree	86

LIST OF FIGURES (continued)

Figure	Title	Page
46	Experimental Retention of the Impacted Liquids on the Dowel Tree Wrapped with Green Ivy Leaves	88
47	Approximate Average Film Thickness of the Retained Liquid on the Dowel Tree Wrapped with Green Ivy Leaves . .	89
48	Experimental Retention of the Impacted Liquids (Small and Large Drops) on the Dowel Tree Wrapped with Green Ivy Leaves	90
49	Approximate Average Film Thickness of the Retained Liquid (Small and Large Drops) on the Dowel Tree Wrapped in Green Ivy Leaves	91
50	General Appearance of the Pine Needle Tree Structures . .	93
51	Experimental Retention of the Impacted Liquids on the Pine Needle Structures	94
52	Product of the Film Thickness and Surface Area of the Retained Liquid on the Pine Needle Structures	96
53	General Appearance of the Juniper Tam Trees	97
54	Experimental Retention of Impacted Water, Fire-Trol 931 and Fire-Trol 100 on Small Juniper Tam Trees	99
55	Experimental Retention of Impacted Water and Phos-Chek XA on Small Juniper Trees	100
56	Measured Average Film Thickness Relative to that of Water on Small Juniper Tam Trees	101

LIST OF TABLES

Table		Page
I	Experimental and Theoretical Mass Mean Droplet Diameter of the Retardants	3
II	Liquid Retained on a Dry Dowel After Central Impact by a Liquid Drop at Normal Incidence	17
III	Approximate Values of the Fluid Properties of the Retardants	19
IV	Liquid Retained on a Dry Dowel After Central Impact by Small and Large Size Liquid Drops at Normal Incidence	21
V	Liquid Retained on a Dry 1/4 Inch Birch Dowel After Central Impact by a Medium Sized Drop at a 45° Angle . . .	24
VI	Liquid Retained on a 1/4 Inch Prewet Birch Dowel After Central Impact by a Medium Sized Drop	26
VII	Drop Evaporation During Fall From the Drop Tower	53
VIII	Measured Maximum Stable Liquid Film Thickness on the Birch Dowel Tree	74

Use of trade or firm names is for reader information only, and does not constitute endorsement by the U. S. Department of Agriculture of any commercial product or service.

SUMMARY

This report describes the results of an investigation of the impaction of individual drops of liquid fire retardant on fuel-simulating dowels, and the effects of the various parameters including retardant rheology on the interaction and fluid retention characteristics.

The studies were conducted by dropping individual drops of retardant with various droplet sizes and fall velocities (controlled by drop height) on different size and composition dowels, model dowel trees and real fuel structures under various conditions, and obtaining information regarding the impact by high speed photography, impactor cards that were located beneath and to the sides of the dowel, and measurement of the liquid mass retained on the structure by means of a sensitive scale. The retardants used in the studies were Phos-Chek XA, Fire-Trol 100, Fire-Trol 931 and water.

The experiments showed that drop impact at high velocity (large drop height) with a dowel produces side splatter, and simultaneously coats a portion of the dowel at the impact site with a film of liquid. For liquids with low effective viscosity (water and the two Fire-Trol fluids) the splatter is in the form of a large number of small drops and spray. For Phos-Chek XA however, which is an elastic fluid, the splatter is in the form of a very few large droplets.

The fractional retention of a liquid drop by a dowel after impact depends on the symmetry of the impact; the retention is greatest for a central impact, and decreases as the impact becomes more off-axis. The retention (and spread area) increases if the dowel is prewet by the retardant (simulating earlier droplet impact), or inclined at an angle other than normal incidence. The fractional retention of the liquid decreases with increase in drop size, but the absolute quantity of retained liquid increases because of the larger drop size. The retention also increases with increase in dowel diameter (for constant drop size).

The high speed photographs showed that the impact of a drop with a dowel causes the liquid to initially undergo a flattening and spreading, followed by fracture of the liquid as it flows laterally off the sides of the dowel in the form of a sheet. For Phos-Chek XA the fracture occurs by a necking of the flowing liquid (due to fluid elasticity), but for the other liquids the fracture occurs by a sudden clean breaking of the liquid across its entire width. At high impact velocity the liquid retention on a dowel is independent of fluid properties, but at low velocities (low drop height or small drop size) Phos-Chek XA has the greatest retention due to its elasticity which retards the flow and fracture of the spreading liquid. The liquid retention at low impact velocity is greater than at high velocity for all of the liquids.

It was also found that the fuel surface properties can affect the liquid retention. A smooth polyethylene (PE) dowel retains more liquid than a not-quite so smooth birch dowel, and this results because the smooth surface allows a partial wrap around of the liquids (except Phos-Chek XA) and exposes a greater retention area to the flowing liquid. The spread liquid on PE is not stable however (PE is inert), and quickly contracts into small drops and ligaments that are then retained on the dowel.

After the single dowel experiments, wetting studies were conducted on model trees made up of dowels. The liquid wetting of the trees occurs by droplet impact, splatter, run and drip. The increased retention found for PE (over birch) after single drop impact was not observed for liquid retention in the tree. This is because the liquid pieces formed by film contraction undergo growth due to subsequent droplet impacts, and gradually leak off the tree. The tendency for liquid run-off of the liquids on the PE tree correlates with the effective viscosity of the fluids at low shear rates, i.e., high viscosity (also high yield stress) increases the fluid retention and average film thickness. Surface roughness had little effect on the fluid retention.

On the other hand for the birch tree, there was no direct correlation of liquid retention with fluid properties, and drop size had little effect on the retention. The results (in comparison with PE, whose surface is inert) indicates that the fuel composition (in conjunction with fluid properties) controls the liquid retention (surface roughness is probably also of some importance). The results with the birch and PE trees (and also the real fuel structures to be discussed) also showed that the overall wetting of a tree occurs in a stratum (layered) fashion.

The studies then progressed to real fuel structures, which consisted of a model tree made up of green willow (with bark) dowels, a tree whose dowel limbs were wrapped with green ivy leaves, and a tree with clusters of pine needles. The experiments concluded using a real plant (Juniper Tam). The experimental results in these cases showed again that the liquid retention does not correlate directly with the fluid properties, and that the fuel composition is of importance. Drop size also again did not affect the wetting of the rigid model trees, but had a small effect on the needled structures.

An analytical approach is described in which it is shown that the results of model fuel experiments such as conducted on the present program can ultimately be used to make predictions regarding the wetting behavior of a real fuel complex by a real retardant rain. The model requires additional experiments and analysis to bring it to completion, and the necessary additional work is discussed.

1. INTRODUCTION

The ability of a dispersed liquid retardant to suppress an advancing fire front in a fuel complex depends on the ability of the retardant droplets to wet or coat a large proportion of the fuel with a sufficient quantity of retardant salt. However the characteristics of the wetting-out process can depend on various properties of both the fuel and retardant droplets, and little is known regarding the penetration, distribution and retention of the retardant as it interacts with different types of fuel elements, and the effects of the physical and rheological properties of the retardant on the overall wetting-out of the fuel.

Early studies by the U. S. Forest Service and others[1-3] (see also the references in Ref. 1) provided evidence that the addition of a thickening agent to water or a liquid retardant can improve both the aerial drop characteristics of the fluid (by increasing the droplet size) and the ability of the fluid to coat the fuel. However it was found that not all thickeners act alike, and that certain types are clearly superior to others in improving the dissemination characteristics of the fluid. The reason for the differences was not known, and the results led the Forest Service to sponsor a program with Shock Hydrodynamics whose overall purpose was to establish the relationships between the rheological properties of a liquid retardant and the aerial drop (dispersion) behavior and subsequent fuel-wetting capabilities of the retardant. The first of these objectives has now been attained[4-6] (to be discussed).

On the other hand the results of the early field tests and continuing field experience have not provided clear or consistent evidence regarding the overall effect of retardant rheology on the wetting-out process. However these tests together with other studies (see Section 9, Ref. 4) have demonstrated that retardant rheology can have an effect (whose relative importance however may depend on various conditons), and that these effects may be useful in controlling the wetting-out characteristics of the fuel in some situations. For example in fighting brush fires below tall crowned trees it is desirable that the dispersed retardant run off the tree crowns onto the ground cover; whereas for open (non-covered) fuel the retardant should stick directly to the fuel.

In preliminary studies conducted earlier on this program,[4-6] it was demonstrated that the impaction and flow characteristics of individual retardant droplets impacting on various surfaces depend on the rheological properties of the retardants. These studies indicated an approach based on high speed photography and sensitive weighing toward further understanding the dynamic interaction of retardant droplets with the fuel.

The purpose of the present program then was to investigate the wetting-out characteristics of fuels by retardant, based on measurement and evaluation of the individual and cumulative effects that successive individual liquid drops have on the overall process. The objective was to elucidate the effects of retardant rheology on the wetting-out process.

1.1 SCOPE OF THE PRESENT PROGRAM

The program consisted of several general work tasks, and was designed to provide information regarding various aspects of the fuel wetting process ranging from the characteristics and effect of single droplet interactions with fabricated dowels to the cumulative effects of many droplets interacting (consecutively) with real fuel structures. In the initial studies, information was obtained regarding the behavior of single droplet impact with a dowel including the effects of retardant rheology and droplet size, dowel composition, size and pre-wetting, and impact angle and orientation. Later studies considered the effects of consecutive droplet interaction with 3-dimensional dowels that simulate actual fuel structure, and this was followed by similar studies with real fuel structures. The results of the studies were correlated with the controlling factors, including retardant rheology, and the rudiments of a quantitative model developed which, when completed, will allow quantitative predictions to be made regarding the wetting out behavior of fuels by a retardant rain.

2. BACKGROUND AND NATURE OF THE PROBLEM

The aerodynamic dissemination of a bulk liquid fire retardant results in the formation of a rain of the retardant which eventually falls on the fuel complex and causes a wetting-out of the fuel. This rain has a relatively short duration however (e.g., 5-15 sec), whose value depends on the droplet sizes (fall speed) of the retardant and the drop altitude. Large droplet sizes and small drop heights result in short settling times for the retardant cloud. During the settling, a quantity of liquid whose total eventual localized ground concentration ranges from less than 1 gpc* to values of 5 gpc or more - depending on conditions - falls on the fuel, which corresponds to about 0.016 to 0.08 inches of liquid. The ground concentration of liquid retardant required to prevent fire propagation through a fuel complex depends on the type and concentration of the fuel as well as other factors such as pattern width and wind conditions. For orientation purposes, the following quantities of a typical retardant have been deduced to be representative of the effective levels of retardant coverage required for various diverse fuel types:[7] tall grass (0.5 to 1 gpc), chaparral (4 to 5 gpc), crowned trees (2 to 5 gpc) and forest litter (3 to 4 gpc).

2.1 DROPLET SIZES OF AERIALLY - DISPERSED RETARDANTS

As noted before, retardants with different thickening agents form different droplet sizes when disseminated by an aircraft. The droplet sizes of water and several retardants were determined experimentally and

---

* gpc indicates the localized surface concentration of liquid retardant in gallons per 100 square feet of ground area (1 gpc is equivalent to about 0.0160 inches of liquid).

correlated theoretically on the earlier studies,[6] and are summarized in Table I for orientation purposes.

TABLE I. EXPERIMENTAL AND THEORETICAL MASS MEAN DROPLET DIAMETER OF THE RETARDANTS IN AND NEAR THE EFFECTIVE GROUND PATTERN (From ref. 6)

Retardant	Drop Speed (knots)	Mass Mean Droplet Diameter (mm)			
		Experimental*			Theory**
1.6 Phos-Chek XA	130	8.7	6.4±1.5	8.2	6.5
Phos-Chek XA	130	5.2	4.8±0.9	5.2	5.2
Phos-Chek XA	180	4.6	4.6±0.9	4.5	4.0
0.42 Phos-Chek XA	130	3.4	3.6±0.4	3.5	3.5
Fire-Trol 100	130	2.6	2.5±0.4	2.5	2.3
Fire-Trol 931	130	2.3	2.3±0.2	2.2	2.1
Water	130	1.6	2.0±0.4	2.0	0.6

* The three columns show the values obtained by three different methods of averaging the experimental data.

** The theoretical values are normalized to the experimental value obtained for 0.42 Phos-Chek XA.

The 0.42 and 1.6 Phos-Chek XA retardants are the standard Phos-Chek XA retardant in which the gum thickener concentration is a factor of 0.42 and 1.6 that of the standard formulation. The mean droplet size may thus be seen to increase with increase in thickener concentration. It decreases with increase in aircraft speed.

2.1.1 Effect of the Physical and Rheological Properties of the Fluid

On the basis of theory and some experimental data given in the literature it was deduced that the mean droplet size of the dispersed retardants at constant aircraft speed should vary proportionally with the quantity, $(\eta_e \sigma/\rho_l)^{1/3}$;* where σ is the liquid surface tension, ρ_l is liquid density and η_e is the effective viscosity of the fluid given by[4]

$$\eta_e = \eta(1 + s) \qquad (1)$$

* This (approximate) expression assumes complete breakup of the liquid, and is valid under drop conditions that the surface erosion (aerodynamic stripping) of the liquid is completed before droplet impact with the ground.

where η is the apparent viscosity and s is the elastic strain (recoverable shear) of the fluid. The value of η and s, and hence η_e, depends on the shear rate for a non-Newtonian fluid and hence the droplet size calculation must include the affect of the shear rate of the liquid during its aerodynamic surface stripping into droplets. Using the derived theoretical shear rate expression and the experimental η_e vs $\dot{S}$ data ($\dot{S}$ is the shear rate) obtained on the program gave quite good agreement between the theoretically computed mean droplet sizes of the various retardants and the experimental values, as may be seen in the table. The droplet size data given in the table are mass mean diameters. In the actual dissemination of a fluid a distribution of sizes about the mean value (both larger and smaller) are produced, and the various experimental and theoretical values are discussed in ref. 6.

2.1.2 Relation to Fuel Wetting by the Retardant

The preceding results explain the differences in droplet sizes obtained by the use of different thickeners. Thus for example, experimental measurements show that Fire-Trol 100 - which is a clay-thickened retardant - is a non-elastic liquid and its large apparent viscosity at low (Brookfield viscometry) shear rates is so reduced by shear during its aerodynamic stripping into droplets that its droplet size and drop characteristics are quite similar to water or unthickened retardant. On the other hand Phos-Chek XA - which is a gum-thickened retardant - is an elastic liquid, and the elasticity causes the effective viscosity of the fluid to remain relatively high during the droplet stripping process, which results in a much larger droplet size than for the Fire-Trol fluid. A gum-thickened retardant is thus clearly superior to a clay-thickened retardant insofar as the droplet size that is produced is concerned.

On the other hand there are a variety of processes that are involved during the wetting of a fuel by a retardant rain, and these may be affected in different manners by the viscosity, elasticity and surface tension of the liquid. Moreover the shear rates involved in these various processes may differ, and may change with time. In addition to the effects that these fluid properties may have on the fuel wetting by the retardant, the sizes of the falling droplets that interact with the fuel will be different for retardants with different properties, as just discussed. It is thus evident that the fluid properties - especially the rheological properties - may relate to the wetting-out of a fuel in a complex manner and that may depend on various conditions. It is the elucidation of this problem that the present program was concerned with.

2.2 FUEL WETTING BY A DISPERSED RETARDANT

Various studies have shown that the wetting-out of a fuel by either an ordinary rain[8] or an aerially dispersed retardant[7,9] occurs by a combination of droplet impact, run and drip. However due to the relatively short lifetime of a retardant rain, the fuel may not become completely or uniformly covered by the retardant. During the rain, the top portion of a fuel usually undergoes more direct interaction with the falling retardant

droplets than the bottom portion, which - depending on conditions - may receive most of its liquid by means of drip and run from the upper portion of the fuel. Depending then on the characteristics of droplet impact (e.g., liquid retention, splatter, etc.), the ability of the liquid to run and drip (related to fluid rheology) and the droplet size and duration of the retardant rain, the fuel will undergo wetting-out in a manner that at any time during the rain flow the coverage of the fuel by the liquid (and possibly the localized fluid concentration, e.g., film thickness) will vary, i.e., will not be uniform, in the vertical direction. Consequently the final liquid coverage (and localized concentrations) after the cessation of the rain and drip from the various elements of the fuel may also vary, and contain a gradient or maximum in the vertical direction. It is anticipated that this vertical distribution (and its time dependence) will depend - among other factors - on the rheological properties of the retardant.

2.2.1 Liquid Storage on Fuel

The accumulation and redistribution of liquid on the surface of a fuel during its wetting by a rain causes a storage of liquid on the fuel which will be partially or wholly retained after the cessation of the rain. This storage is often expressed in terms of an equivalent film thickness, as suggested originally by Grah and Wilson.[10] The equivalent film thickness is that average thickness of liquid that would be obtained if the liquid stored on the fuel were redistributed uniformly over all the area of the fuel. By conducting the storage experiment on a common fuel or fuel element (where the surface area remains constant) it is possible to measure the relative weights of different liquid retardants which can be stored on the fuel, and thus the relative storage effectiveness of liquids without the uncertainties inherent in the measurement of the fuel surface area.[4]

The amount of liquid that can be stored on a fuel depends on the conditions.[10] The storage of liquid on a saturated fuel subjected to a rain flow is called "transitory storage", and the value depends somewhat on the intensity of the rain. If the rainfall is stopped and the fuel allowed to drip until the excess liquid is removed, i.e., until the drip ceases, the term "conditional storage" is used to describe the storage. Finally if the fuel is shaken (corresponding to wind movement) to remove the loosely bound liquid, the term "residual storage" is used to describe the remaining stored liquid. This liquid is securely bound to the fuel and can only be removed by evaporation. For orientation purposes, it has been found in several studies involving the wetting of branched wood by a water rain that the percentage of liquid held by the fuel in storage is very roughly the same in each of the three storage conditions, i.e., about one-third of the total stored water under saturation conditions is subsequently lost by drip, an additional one-third is lost by shaking, and one-third remains firmly bound. This relative constancy does not appear to be valid for viscous retardants, however.

It has been found[4,9] (also in studies by the Forest Service) that the amount of liquid stored by a fuel, i.e., the equivalent film thickness, is significantly greater for a thickened retardant than for water (e.g., by

a factor of 4 to 15 depending on various factors). This is consistent with the statement that[1] "viscous agents were first incorporated into aerial and ground retardant formulations for the purpose of providing better adherence of the retardant to the fuels and to minimize the runoff". However gum-thickened retardants are elastic as well as viscous, and little is known regarding the relative importance of the viscosity and elasticity (which are both shear rate dependent) in the wetting-out of the fuel. It has been said that polymeric thickening agents add strength and consequently thickness to films applied to vertical fuel surfaces.[11]

2.2.2 Effect of the Physical and Rheological Properties of the Fluid

Studies have been conducted for some years to determine the effectiveness with which a fire can be extinguished by the direct application of water that contains an additive (called a short term retardant). For example, "wet water" is produced by the addition of wetting agents, e.g., certain detergents, which lower the surface tension so that the water can spread easier on a surface and also penetrate easier into smaller cracks. Of more importance however, are rheological additives (e.g., clays and certain gums and polymers) that increase the viscosity[12] and cause the water to stick or adhere more easily to the fuel, and be retained in greater thickness. Water thickened with these types of additives is sometimes called "viscous water", "sticky water" or "slippery water". In either of the above cases the main purpose of the additive is to increase the efficiency of the water in extinguishing the fire.

In the case of aerial fire fighting however, it has been found more effective to utilize retardant additives which themselves alter the ignition and combustion mechanism of the fuel in order to retard or prevent the flame spread. The overall better substances for this purpose have been found to be certain salts used as commerical fertilizers, including diammonium phosphate and ammonium sulfate. In this case the water is used largely as a vehicle to coat the fuel with the retardant salt - which is the dominant fire fighting ingredient - and the retardant is therefore called a "long term" retardant since the presence of the water is not necessary to retard the flame spread. In the use of the retardant, however, a rheological thickener is usually also added to improve the drop characteristics (droplet size) as well as the fuel-coating characteristics of the liquid retardant. The first of these, i.e., the effect of the thickener on droplet size is now understood in a semi-quantitative manner, as discussed previously.

The second purpose of the rheological thickener is to improve the retention of the liquid retardant on the fuel so that the requisite quantity of retardant salt is deposited on the fuel after the evaporation of the water. In this case the purpose of the thickener is related to that used in short term retardants except that the desired coating ability of the retardant is for the purpose of salt deposition rather than enhancing water layer

thickness (depending on various factors, both the retardant salt and water film may contribute to impeding the flame spread in the use of a long term retardant). The general effectiveness of a long term retardant in impeding flame spread is thus related to the wetting-out characteristics of the fuel by the retardant, and these characteristics are determined both by the physical and rheological properties of the liquid retardant (which are largely controlled by the thickening agent) and various properties of the fuel.

2.2.2.1 Vertical Fuel Coverage

As discussed before, fuel wetting by a water or fire retardant rain takes place by a combination of droplet impact, run and drip. During the wetting, a mass balance can be used to describe the partitioning of the falling liquid as it interacts with the fuel complex.[8] Thus of the total amount of liquid that falls on a fuel, a portion passes directly through the fuel without any interaction, another portion remains stored on the fuel while some passes through the fuel by means of drip and stemflow, and some liquid (but not the salt) may leave the fuel by evaporation. A variety of processes and factors are in principle involved in the wetting-out of a fuel by a retardant rain, but the general complexity of the events has prevented many of the individual processes to be taken into consideration in attempting to model the wetting of a fuel. For example, in most studies involving the wetting of forest fuels by rain the relative importance of the mass partition terms has been determined experimentally without regard to the various processes that occur and actually give rise to the partitioning. These studies have shown that the role of stemflow is usually of minor importance, and that depending on fuel conditions, the fraction of liquid that passes without interaction through the fuel can vary widely.

On the other hand it has been possible to take some of the preceding factors and processes into account in an indirect manner. Swanson and Helvig for example developed a vertical fuel coverage model as a method of providing estimates of the vertical fuel effect on required retardant quantities.[9] This model by-passed the actual processes involved in the droplet impaction, flow and drip of the liquid but took them into account in an indirect and approximate manner by utilizing the Grah-Wilson film concept of liquid storage. The characteristics of the wetting-out of the fuel in this model thus depend on the probability of direct droplet impact with the various elements of the fuel together with liquid transfer between various fuel strata by drip when the elements become saturated (in the Grah-Wilson film sense). The model can be calibrated from experimental data, and the effects of fluid rheology are included by the use of experimental film thicknesses of the retardants. This model is of some interest and predicts a number of realistic features of the wetting-out of a fuel by a retardant rain. It also has certain deficiencies.

It is well recognized that the physical and rheological properties of a retardant can affect the fuel-wetting process in various ways, even though the overall effects and how they change with conditions are not clear. For example these properties (at constant aircraft speed) determine the droplet sizes of the dispersed retardant, as discussed previously; and

different droplet sizes have different impact velocities. Both of these factors (size and velocity) affect the breakup of the droplet when it interacts with the fuel (as discussed in Section 9 of ref. 4), and should thus relate in some manner to the efficiency of the direct retention of the liquid by the fuel. For sufficiently small droplets which do not undergo breakup at impact the empirical equation of Sell[13] is often used[14] to describe the collection efficiency, E, of the droplets with diameter, D, impacting with velocity, V, with a cylindrical element with diameter d, i.e.,

$$E = 2.84(10^{-4})\ D^2V/d \qquad (2)$$

where E is %, D is microns, V is cm/sec and d is cm. On the other hand large drops passing through fine fuels such as tall grass may deflect the fuel and pass through intact. Between these extremes a droplet will breakup upon impact with the fuel and a portion of the liquid will be retained on the fuel element in the vicinity of the impact. Depending on various factors, the fraction of the liquid that is retained should depend on various properties of the liquid drop.

The droplet size can also have other effects on the fuel wetting process. Thus the size of the droplets will affect the chances of a droplet interacting with an element of the fuel during canopy penetration. The droplet size together with drop height also determine whether the retardant rain has a forward-moving component as it interacts with the fuel. Some studies have suggested[7] that a vertical rain is best for retardant application.

The physical and rheological properties of the retardant also affect the coating of the fuel (film thickness and coverage levels) as mentioned several times earlier, although the relative importance of the various properties (e.g., viscosity, elasticity, surface tension, bonding strength) are not generally known or how they depend on conditions. These effects are of special importance for fine fuels ($\leq$ 1/2 inch), since the effect of retardants on the retardation of flame spread is dominated by the fine fuels rather than the branch-woods.[9]

The fuel properties can also have important effects on the fuel-wetting capabilities of retardants. Anderson of the Forest Service conducted studies on the transmission of aerially-delivered fire retardant through vertical fuels.[15] He found that the fraction of retardant retained on the fuel increased as the fuel diameter and surface roughness of the fuel was increased. It is also known that surface composition, fuel geometry and other fuel properties can affect the wetting-out characteristics.

2.2.2.2 Retardant Rheology Tradeoff Considerations

As discussed earlier, a thickener is added to a fire retardant solution to improve both the drop characteristics (droplet size) and the coating of the fuel by the retardant. However these are independent

processes, and the optimum concentration of thickener is not necessarily the same for both processes. It is desirable in practice to adjust the thickener concentration in a manner as to achieve the best combination of retardant dispersion and fuel coverage, which however may vary somewhat depending on various factors. A suitable understanding of the effect of retardant rheology on the fuel-wetting process in conjunction with that presently available on the effect of retardant rheology on droplet size should enable the rheology tradeoff effects to be evaluated.

3. BEHAVIOR OF A LIQUID DROP IMPACTING WITH A DOWEL

As noted earlier, the purpose of this program was to investigate the wetting-out characteristics of fuels by liquid fire retardant, with the view toward elucidating the effects of retardant rheology on the wetting-out process. The general approach was based on the measurement and evaluation of the individual and cumulative effects that successive individual liquid drops have on the overall process. As a first step toward this goal, studies were conducted on the behavior of individual drops of retardant impacting with a dowel and are discussed in this section. Previous studies have examined the spreading characteristics of drop impact with a flat wood or paper surface,[4-6] and some preliminary information was also obtained using a wooden dowel.[5]

3.1 GENERAL APPROACH

The experiments consisted of dropping individual drops of retardant with various droplet sizes and fall velocities onto a dowel under various conditions, and obtaining information regarding the impact by high speed photography, impactor cards that were located beneath and to the sides of the dowel, post inspection of the dowel and cards, and measurement of the liquid mass retained on the dowel (by a sensitive scale). The retardants used in the studies were Phos-Chek XA, Fire-Trol 100, Fire-Trol 931 and water, whose rheological properties encompass a wide range. An easily obtained medium drop diameter of 4 to 5 mm was used for all the retardants in many of the experiments, but in some studies small (~ 2 mm) drops were used in addition for the low viscosity fluids and large (7-8 mm) drops for the fluids with high viscosity. The impact velocity of the drops in many of the tests corresponded to that obtained by dropping the drops a distance of approximately 42 feet (from a drop tower) before they impacted with the dowel, which gave essentially full terminal velocity to the impacting drops. In some cases however the drops were dropped a distance of only approximately 2 feet to give a smaller impact velocity.*

The cylindrical dowels used in the studies were made of 1/4 and 1/2 inch diameter smooth birch to simulate a fine fuel and study size effects, and 1/2 inch diameter polyethylene to study fuel composition effects. The dowels were positioned in the horizontal (0°) position, and also at 45° (with respect to the horizontal plane) to study the effect of impact angle. Both axis and off-center impacts were studied, and impacts were made on both dry dowels and dowels that had been prewet with the retardant (to simulate droplet impact after the surface had been wet by a previous impact).

* The change in drop heights may result in small differences in the shape of the impacting drops. However the effects of drop shape are trivial compared to the change in the impact pressure, which largely determines the spreading behavior of the impacting liquid.

3.2 EXPERIMENTAL SETUP AND PROCEDURES

The experiments were conducted by dropping individual drops of retardant onto a dowel that was mounted on a small stand. Except for the high speed photographic studies, the dowel was mounted on a sensitive scale in a manner that the liquid remaining on the dowel after the impact could be weighed immediately before any weight loss incurred by evaporation.

3.2.1 Dowel Weighing

The scale used for the dowel weighing procedure was the Arbor Model 506 Electronic Balance, manufactured by Arbor Laboratories Incorporated, and having dimensions of 16-3/8"x9"x10-1/2". A few of its special features include a digital readout, a tare function and a time integrator control that determines the length of time between display updates. Using the tare switch allows the reading of the liquid mass that is retained on the dowel after droplet impact. The capacity of the scale is 675 grams and its sensitivity is 1 milligram with a precision of 0.5 milligram.*

In the experiments using the drop tower, the scale was placed inside a 2'x2'x3' plywood enclosure with a plexiglas front (see Figure 1a) to prevent airdraft from interfering with the scale readings. It was set on the concrete ground base to insure stability against vibration. The top of the enclosure contained an 11-inch diameter circular opening on which rested the 12-inch diameter, 40 foot long galvanized metal tube through which the liquid drops were dropped. The top of the tube was covered with a movable piece of plexiglas, which contained a 1.25-inch diameter hole through which the drops were introduced into the tube.

In order to prevent the scale from becoming contaminated with retardant when the falling drops missed the dowel and also allow only the liquid actually retained on the dowel to be weighed, a 0.035-inch thick metal shielding plate mounted on legs was used to cover the scale (Figure 1b,2). The plate contained two 1/4-inch diameter holes located 2-7/8 inches apart above the weighing pan of the scale through which two toothpicks supported the dowel (located above the shield) on its stand, which rested on the weighing pan.

3.2.1.1 Weighing Procedure

With the dowel weighing setup as shown in Figures 1 and 2, and using the tare function to give zero readings initially, when a drop impacted on the dowel, the individual weight readings on the readout versus time were plotted as illustrated in Figure 3. The initial high reading is due to the drop impact, and it is the subsequent plateau values that represent the weight of the retained liquid. In this particular case the weight of the retained liquid was considered to be 39 mgm. After sufficient time, the weight of the retained liquid would decrease, due to evaporation. The time at which this occurred as well as the rate of weight loss depended on various factors.

* The dimensions, capacity and sensitivity of the scale helped determine the size and weight of the model trees that were used in the studies.

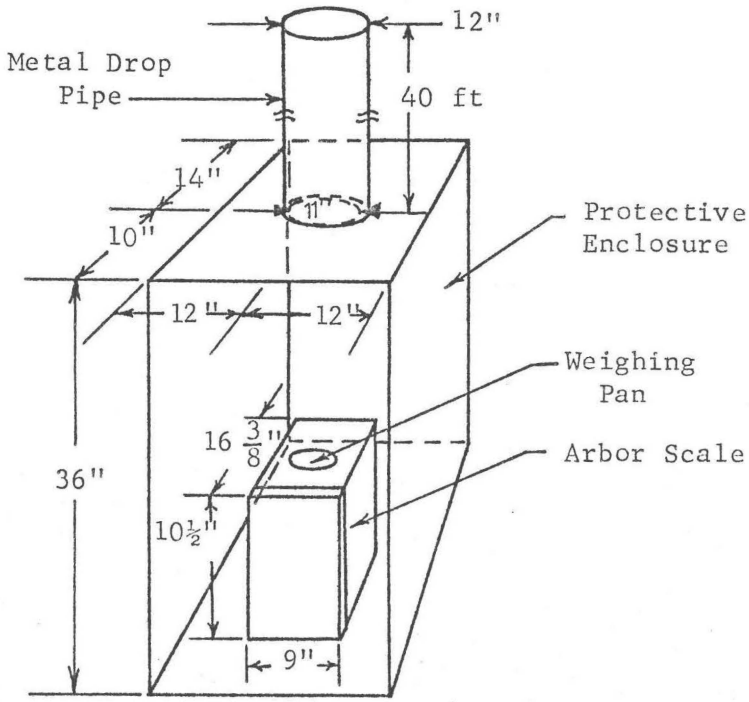


Figure 1a. Experimental Setup for the Dowel Weighing Experiments

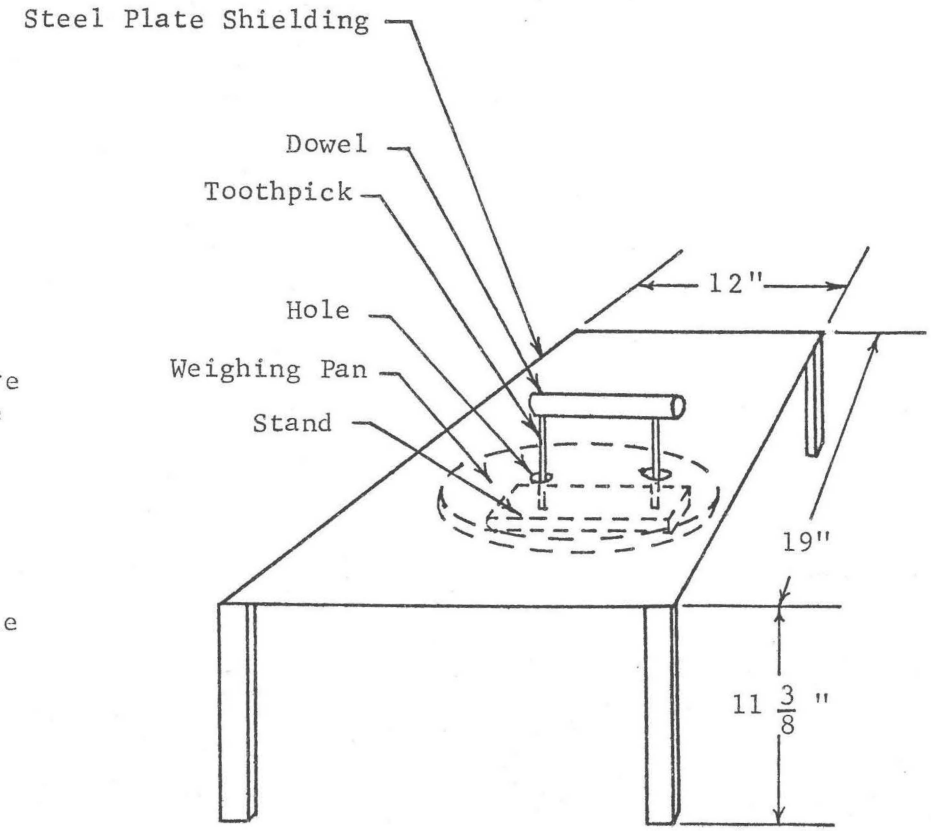


Figure 1b. Scale Shield and Mounted Dowel

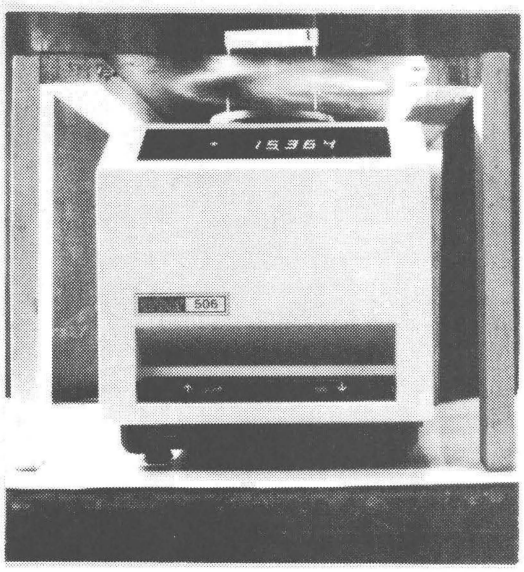


Figure 2a. Arbor Balance With Top Shield, Toothpick Stand and Test Dowel.

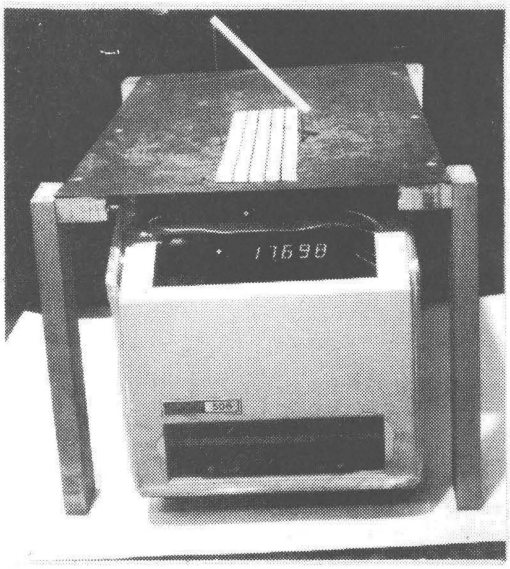


Figure 2b. Setup for 45° Dowel Impact Test.

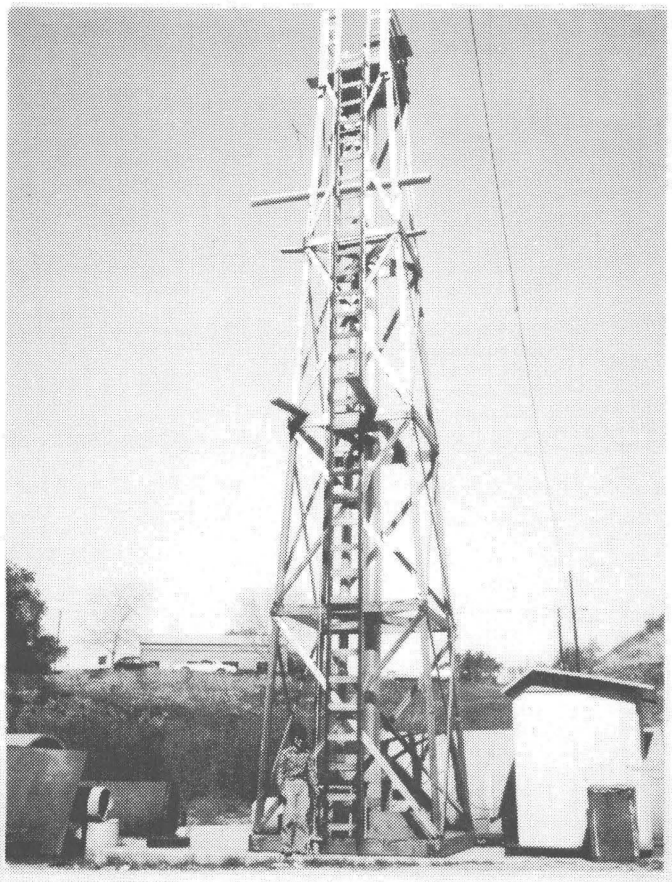


Figure 2c. Drop Tower Used for the 42 ft Drop Tests.

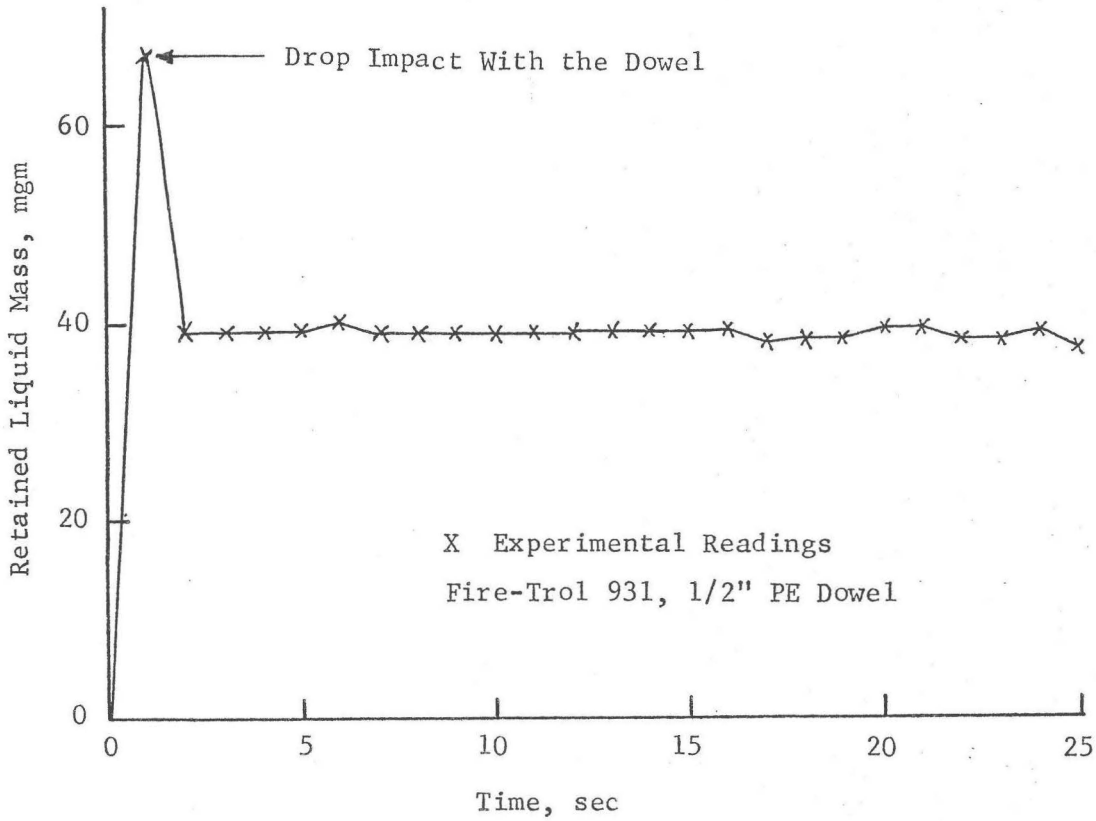


Figure 3. Illustration of the Liquid Mass Readings on the Arbor Balance vs Time

3.2.1.2 Experimental Difficulties

Due to temperature gradients within the inside of the 40 ft long drop tube and possibly other factors, the drops usually did not fall straight down but rather appeared to follow a random (in some cases possibly spiral) path. With the setup as previously shown, and having the dowel lined up as well as possible with the dropper on the top, about 31% of the medium sized Phos-Chek XA drops hit the dowel in some position (i.e., off-center or central), but only about 5% of them hit the dowel on the center. About 70% of Fire-Trol 931 drops hit the dowel, off-center plus central, and only 9% of them hit the dowel on the center. Fire-Trol 100 was the hardest solution to aim, and only about 6% of the drops hit the dowel and 0.8% hit it on the center. A large number of drops were thus dropped in the studies, since about 3 to 7 successful impacts were obtained and averaged for each particular test condition.

At 2 ft drop height, the reduced drop height eliminated most of the drift and made aiming much easier. The percentage of central impacts in this case increased to 35% to 75% for the various retardants.

3.2.2 Splatter Pattern Observations

To obtain information regarding the splatter obtained from retardant droplets impacting with various fuel elements, an impactor (splatter) card of 8 x 2.5-inch dimensions, with 1/4-inch square drawn grid lines was placed centrally below the dowel. These cards were made of the same paper (glossy side up) as used in the studies of ref. 6. The splatter (or witness) card in a test was 2.5 inches below the top of the dowel, and rested on the steel plate. Thus its weight was not on the scale, which after a test enabled the weight of the liquid retained on the dowel to be determined.

The splatter card (and dowel stain) also provided evidence regarding whether a central (axis) or an off-center impact was produced in a test.

3.2.3 High Speed Photography

The high speed photography experiments were conducted to provide visual information regarding the behavior of a drop of retardant during its impact interaction with a dowel. In photographing the event, a photodiode was used to detect the droplet at some distance before it interacted with the dowel (Figure 4) and trigger the delay unit, which delayed the actuation of the flash lamp until just before the drop began to interact with the dowel.

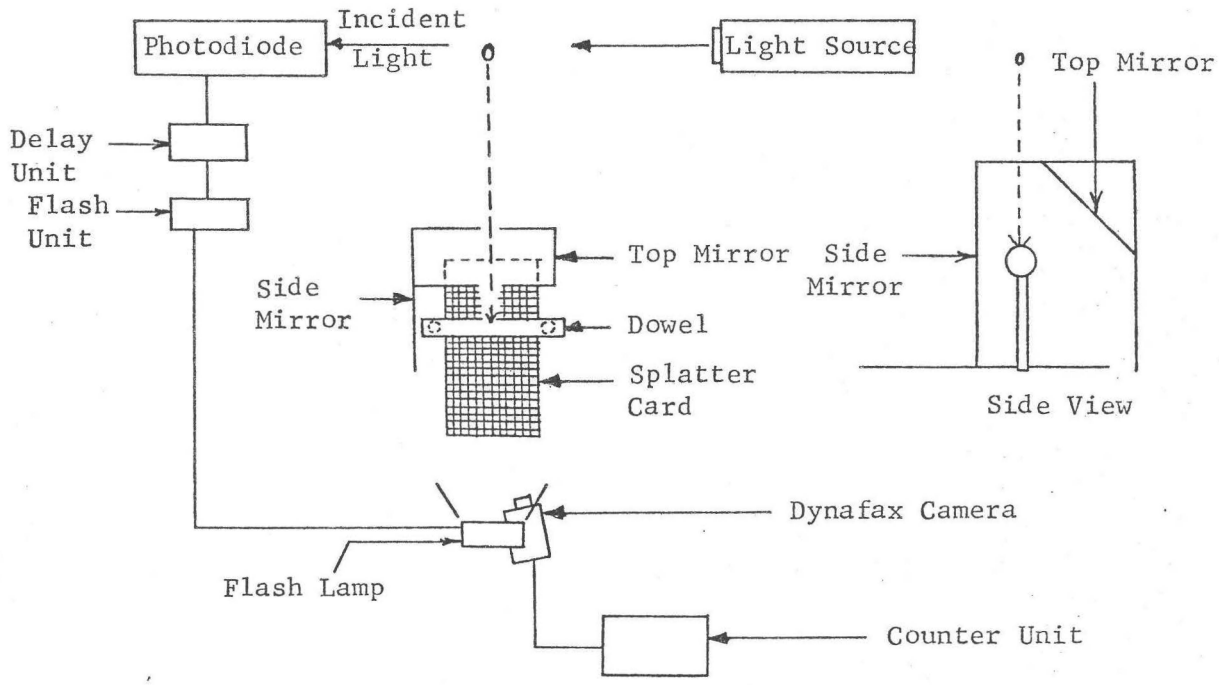


Figure 4. Experimental Setup for Photographing the Impact of a Falling Drop With a Dowel

A Dynafax camera was used to take pictures of the impact event, and a system of two mirrors was used which enabled the top and two side views of the target area to be photographed simultaneously. Under the experimental setup conditions, about 23 msec of the event could be observed photographically.

3.2.4 Fire Retardant Preparation

The retardants Phos-Chek XA, Fire-Trol 100 and Fire-Trol 931 were prepared in the same manner as in the previous programs.[4] The water used in studies was stained for visual purposes by adding 15 drops of India ink to every 50 mℓ of distilled water.

3.2.5 Liquid Drop Preparation

As noted before, three different sized drops (~ 2, 4-5 and 7-8 mm diameter) were used in the studies. Emphasis was given to the use of the medium sized drops, due to their relative ease of preparation. However some studies were also conducted with smaller and larger size drops of particular retardants in order to more closely simulate in some cases the actual mean droplet sizes produced in the field, as given in Table I.

The different size drops of the various retardants were obtained using different size eyedroppers. The ordinary eyedropper available commercially was used for the medium size drops, whereas the other two sizes were constructed by drawing glass to give the proper size orifice. Some difficulty was experienced in the preparation of the smaller drops in that the Fire-Trol 931 fluid occasionally tended to become clogged in the orifice, and the tips of the eyedroppers were fragile and broke easily during use. A 27 gauge hypodermic needle was also used to prepare the smaller drops of water in some cases, but could not be used for Fire-Trol 931 because of clogging.

In practice it was attempted to keep the generation of each drop as consistent as possible. The drop size of each retardant from a particular eyedropper was determined on each particular day that retardant was used by dropping about 10 or more drops individually from the top of the drop tower into a cup that was located on the weighing pan of the scale, weighing each drop and averaging the results. For example in one case, for the medium size drops of Fire-Trol 100, the individual drops weighed 71, 70, 68, 73, 73, 67, 68, 72, 71 and 68 mgm. The mean mass of a drop was thus 70.1 mgm, and the standard deviation was 2.234 mgm, or about 3.2% in droplet mass. Using the fluid density of 1.127 gm/cc, the diameter of the mean sized drops in this case was computed to be 4.92 mm.

The results were similarly obtained with the other retardants, but the percentage deviation from the mean was higher and ranged from about 6 to 12%, depending on the fluid and drop size.

3.2.6 Prewetting Procedure

In the prewetting experiments, the dowel was wetted with the retardant before it was impacted with a retardant drop. Since only a small percentage of drops hit the dowel, the prewetting liquid would evaporate during the drops, and consequently the chamber was kept humidified in these tests. Even so, it was sometimes necessary to repeat the prewetting during the dropping.

For water and Fire-Trol 931 the dowel was prewet by immersing it into the fluid and then shaking off the excessive clinging drops. This procedure was not used for Fire-Trol 100 and Phos-Chek XA due to their relatively large viscosity and consequent large film retention (much larger than the retention in the drop experiments). The procedure finally adopted for these retardants was to brush on the upper half of the dowel the amount of liquid mass that gave the same surface density of liquid as was obtained in the dry-dowel liquid retention experiments.

3.2.7 Dowel Impact Angle

The setup for the 45° dowel impact angle tests is as shown in Figure 2. The length of the dowels used in 0° impact angle case was 3 inches long. In order to have the same perceived length in the 45° inclination situation, the dowels used were approximatly 4-1/4 inches long. The splatter card was placed on the horizontal plane, thus making an angle of 45° with the dowel.

3.2.8 Off-Center Impact

Information regarding off-center impacts was obtained from the drop tests in which the falling liquid drop did not hit the dowel in the central axis position.

3.3 EXPERIMENTAL RESULTS AND DISCUSSION

3.3.1 Liquid Retention on Dry Dowels After Normal Incidence Drop Impaction

Several experiments were conducted for every test condition of the liquid retention studies, and the results were averaged. Table II summarizes the results of the liquid retention experiments on a dry dowel (3 inches long) with normal (0°) impaction by the medium sized (4-5 mm) liquid drops. Shown is the experimental average mass retained on the dowel for each test condition, the number of tests conducted for that condition, the standard deviation of the individual test results, and the percentage of the mass of the incident drop that was retained by the dowel after the impact. The results in Table II are shown graphically in Figure 5.

3.3.1.1 Impact Velocity

Two drop heights were employed for dropping the drops on the dowels; 42 ft and 21.3 inches (~ 2 ft). The impact velocity of drops of Phos-Chek XA and Fire-Trol 931 dropped from the drop tower was measured photographically

TABLE II. LIQUID RETAINED ON A DRY DOWEL AFTER CENTRAL IMPACT BY A MEDIUM SIZED LIQUID DROP AT NORMAL (0°) INCIDENCE

Solution	Water	FT-931	FT-100	PC-XA
Drop Diameter, mm	4.2-4.4	4.4-4.5	4.8-5.0	4.4-4.9
Drop Height:	42 ft	1/4 inch Birch Dowel		
Retained Mass, mgm	7.7	9.0	14.7	9.5
Standard Deviation	1.1 (7)*	0.8 (4)	1.5 (3)	0.6 (4)
Liquid Retention, %	20.5	18.1	20.9	17.8
Drop Height:	2 ft	1/4 inch Birch Dowel		
Retained mass, mgm	14.0	16.8	22.8	30.3
Standard Deviation	1.7 (3)	1.3 (4)	3.0 (5)	6.4 (4)
Liquid Retention, %	32.0	33.1	31.1	46.7
Drop Height:	42 ft	1/2 inch Birch Dowel		
Retained Mass, mgm	15.2	17.8	26.3	20.8
Standard Deviation	1.6 (5)	0.5 (4)	2.2 (4)	2.7 (6)
Liquid Retention, %	40.5	35.8	40.8	32.9
Drop Height:	2 ft	1/2 inch Birch Dowel		
Retained Mass, mgm	24.5	32.7	42.6	62.6
Standard Deviation	3.2 (6)	0.6 (3)	5.0 (5)	5.7 (5)
Liquid Retention, %	56.0	64.6	58.1	96.7
Drop Height:	42 ft	1/2 inch Polyethylene Dowel		
Retained Mass, mgm	26.9	34.8	—	33.8
Standard Deviation	3.3 (7)	3.7	—	3.4 (5)
Liquid Retention, %	71.5	70.2	—	72.5
Drop Height:	2 ft	1/2 inch Polyethylene Dowel		
Retained Mass, mgm	34.6	40.5	59.8	62.8
Standard Deviation	6.8 (5)	8.2 (4)	5.4 (5)	4.1 (6)
Liquid Retention, %	79.1	80.1	81.6	97.1

*The number in parenthesis indicates the number of tests.

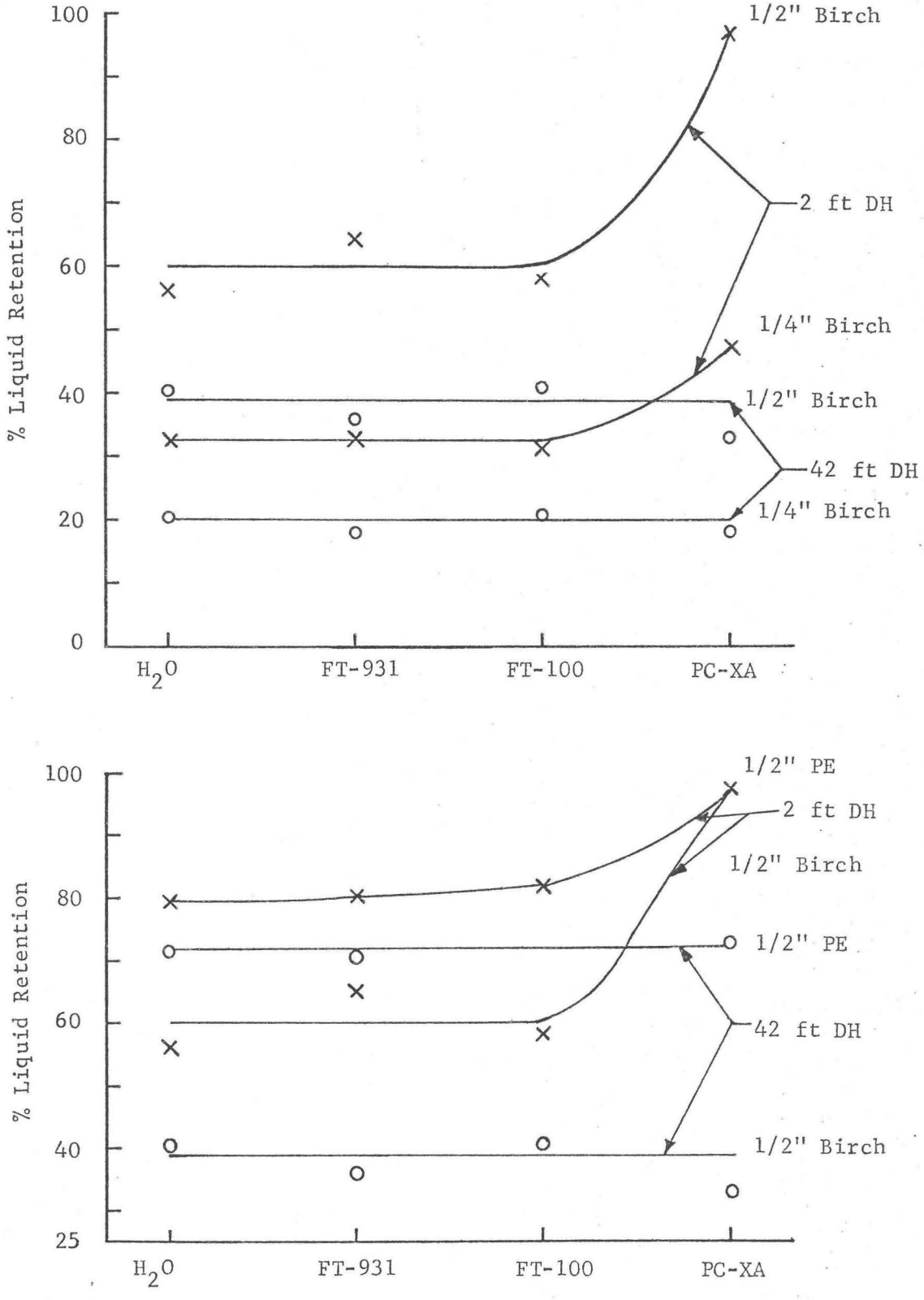


Figure 5. Effect of Retardant Rheology, Dowel Size and Composition and Drop Height (DH) on the Liquid Retained on a Dry Dowel after Central Impact by a Medium Sized Drop at Normal (0°) Incidence

and generally ranged between 26 and 27 ft/sec, which is close to the terminal velocity of the drops. Based on photography, the drops from the 2 ft drop height had an impact velocity of about 10.5 to 11 ft/sec.

3.3.1.2 Fluid Properties of the Retardants

In examining the implications of the experimental results it is useful to keep in mind the values of the various properties of the retardants. These were determined earlier,[4-6] and are summarized in Table III.

TABLE III. APPROXIMATE VALUES OF THE FLUID PROPERTIES OF THE RETARDANTS

Retardant	($\dot{S}$=12 sec^{-1})* η_a (poise)	η_e (poise)	($\dot{S}\simeq$ 550 sec^{-1})** η_a (poise)	η_e (poise)	Surface Tension (dyne/cm)	Yield Stress ($dynes/cm^2$)	ρ_o gm/cc
Phos-Chek XA	13	37	1.0	12.5	46	185	1.07
Fire-Trol 100	19	19	0.6	0.6	92	235	1.13
Fire-Trol 931	1.3	3.3	0.085	0.5	80	20	1.09
Water	0.01	0.01	0.01	0.01	72	0	1.00

* This shear rate corresponds to the Brookfield viscometer value.

** This shear rate corresponds to the value at which the droplets are formed by the wind stripping of bulk liquid at an aircraft speed of 130 knots.

η_a is the apparent viscosity of the fluid, and η_e is the effective viscosity as given in Eq. (1). The effective viscosity contains the combined effects of apparent viscosity and fluid elasticity at the particular shear rate at which process occurs. The shear rate over the more important range of the spreading and fracture of an impacting liquid drop will generally lie between the Brookfield and the surface stripping values shown in the table, but approaches zero near the termination of the flow.

3.3.1.3 Effect of Drop Height and Retardant Composition on the Liquid Retention

Figure 5 shows that at the 42 ft drop height the percentage of the liquid mass of a drop retained on each particular dowel after the impact was approximately the same for all of the retardants. This indicates that at high impact velocities the fluid rheology and surface tension have little effect on the liquid retention over the range of conditions studied. The reason for this is not known, but it implies that the effect of the viscoelastic and surface tension forces on the spreading and breaking of the liquid is small compared to the impact force which imparts a relatively high initial kinetic energy to the liquid.

At the small (2 ft.) drop height (lower impact velocity)

the fraction of the liquid retained by the dowels is greater than at the large drop height for all liquids. In this case however, the percent of retention of the Phos-Chek XA on the dowel was significantly larger than the other fluids, whose retentions were about the same. The high speed photographs (to be discussed later) indicated that this was the result of the elastic forces developed in the liquid during its impact spreading, which resisted the flow and fracture of the liquid and tended to pull some of the spreading liquid back on the dowel subsequent to its peripheral fracture. This explanation is consistent with the fluid properties given in Table III which shows that Phos-Chek XA maintains a high effective viscosity over the shear rate range of interest (due to its elastic forces); whereas the effective viscosity of the two Fire-Trol solutions decrease significantly with increase in shear rate due to shear thinning, and the viscosity of water is naturally small (Fire-Trol 100 is a non-elastic liquid, and Fire-Trol 931 is slightly elastic).

The preceding results indicate that at relatively low impact velocities fluid elasticity can increase the amount of the liquid that is retained on the fuel. This is of some interest since liquid drip between various layered fuel elements can be an important process in the wetting-out of a fuel by a retardant rain, and the impact velocities of the dripping drops are relatively small.

3.3.1.4 Effect of Dowel Size and Composition on the Liquid Retention

Figure 5 shows that at a constant drop height (impact velocity), the percentage of liquid retention increases with increase in dowel diameter. In fact, doubling the birch dowel diameter from 1/4 to 1/2 inches essentially doubled the liquid retention at both drop heights for all of the retardants. This effect is probably due to the increased surface area of the dowel that is in direct contact with the liquid during its spreading and subsequent fracture. Essentially all of the Phos-Chek XA drop remained on the 1/2 inch dowel at the low drop height.

The composition of the dowel can also affect the liquid retention (with all other factors remaining fixed). Thus it can be seen in the table that the percent retention was significantly greater for a 1/2 inch polyethylene dowel than for the 1/2 inch birch dowel at both drop heights, except for Phos-Chek XA at the low drop height which remained about the same since most of the liquid remained in both cases. The result that the retention was greater for the polyethylene dowel rather than less was somewhat surprising, since the plastic dowel was used to simulate a waxy surface such as smooth bark or a leaf. The increased retention of the polyethylene over the birch dowel is believed to be due to the fact that its smoother surface allows the (essentially non-elastic) impacting liquids to wrap around the dowel, as will be discussed later.

3.3.1.5 Effect of Drop Size on the Liquid Retention

In addition to the studies using medium sized (4-5 mm) drops summarized in Table II, some studies were also conducted using both smaller ($\sim$ 2.3 mm) and larger (7.1 mm) sized drops of some of the retardants* The liquid retention results for normal incidence impact with a dry dowel are summarized in Table IV and Figure 6.

* Fire-Trol 100 was not studied at other drop sizes, according to the contract.

TABLE IV. LIQUID RETAINED ON A DRY DOWEL AFTER CENTRAL IMPACT BY SMALL AND LARGE SIZE LIQUID DROPS AT NORMAL (0°) INCIDENCE (DROP HEIGHT IS 42 FT)

Solution	Water			Fire-Trol 931			Phos-Chek XA		
Dowel*	¼" B	½" B	½" PE	¼" B	½" B	½" PE	¼" B	½" B	½" PE
Drop Diameter, mm	2.3	2.3	2.5	2.4	2.2	2.2	7.1	7.1	7.1
Retained Mass, mgm	3.5	5.0	7.5	3.5	4.7	6.0	18.0	35.7	61.4
Standard Deviation	0.7(2)**	0.0(2)	0.6(4)	0.7(2)	0.6(3)	0.0(3)	0.0(4)	4.0(3)	8.0(5)
Liquid Retention, %	53.5	75.2	96.5	45.9	77.8	100.0	9.0	17.8	30.6

* B and PE indicates the birch and polyethylene dowels.

** The number in parenthesis indicates the number of tests.

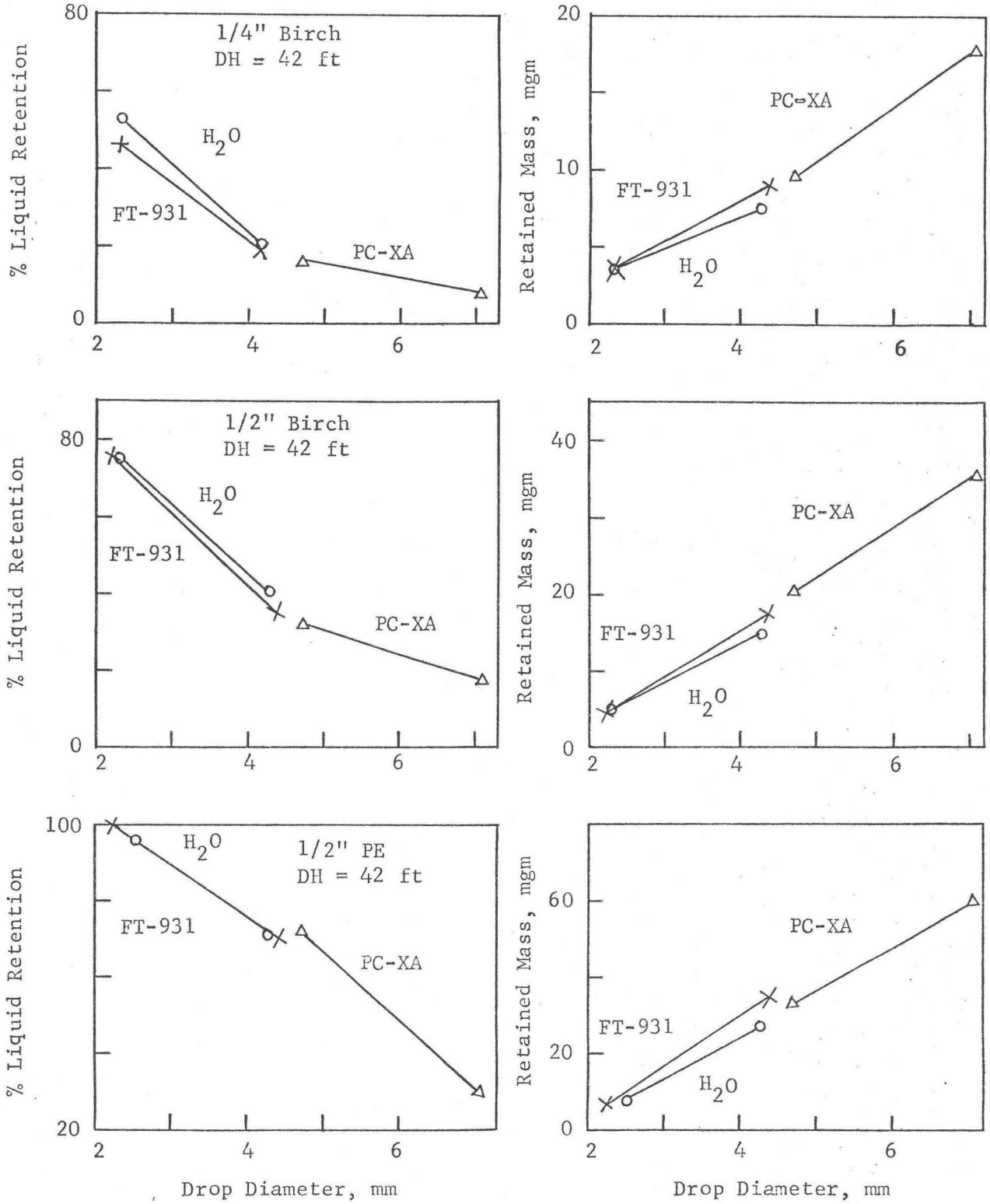


Figure 6. Effect of Drop Diameter on the Liquid Retained on a Dry Dowel After Central Impact at Normal (0°) Incidence.

A drop height of 42 ft. was used in these studies. The impact velocity of the drops was not measured in these cases, but can be estimated from the measurements on the medium sized drops and the effect of drop size on the terminal velocity. On this basis the impact velocity of the small and large sized drops was about 19 and 33 ft/sec, respectively.

A comparison of the results of Table IV with those of Table II (summarized graphically in Figure 6) shows that increasing the droplet size of a particular retardant (for fixed dowel size and drop height) decreases the percent of the mass of the liquid drop that is retained. However, although decreasing the drop size increases the efficiency of the liquid retention process, it decreases the absolute weight of retained liquid (shown also in Figure 6) since smaller drops have a smaller mass. Thus for example, although the percent mass retention of 2.3 mm drops of water on the 1/4 inch birch dowels was 53.5 percent, while the percent retention of 7.1 mm Phos-Chek XA was only 9 percent, the retained mass of the Phos-Chek was 18 mgm whereas the retained mass of water was only 3.5 mgm.

The general effect on the liquid retention of decreasing the droplet size while using a fixed size dowel is essentially the same as increasing the dowel size while using a fixed size drop, i.e., both changes increase the efficiency of the liquid retention process. The absolute value of the efficiency (% retention) depends on the relative size of the liquid drop in comparison to the dowel, as well as on retardant rheology and fuel composition. It is of interest to note (Figure 6) that small drops have a large retention efficiency with sufficiently large dowels (fuels) even at large drop heights.

3.3.1.6 Effect of Drop Size in Aerial Dissemination

As discussed in Section 2.1, different retardants have different drop sizes (see Table I) when dispersed from an aircraft. The studies summarized in Figure 6 show that the efficiency and absolute mass of the liquid retained on a dowel (fuel) after drop impact depends on the drop size. Thus in comparing the liquid retention characteristics of different retardants that are aerially dispersed, the actual drop size of the retardants should be used. On this basis the curves given in Figure 6 (using the appropriate drop size of each retardant) are more applicable than the curves in Figure 5 which are for constant drop size. Using the curves in Figure 6 shows that the percentage of dropped liquid retained by a wood dowel is then greater for water and the two Fire-Trol solutions than for Phos-Chek XA since their droplet sizes in the field are smaller. On the other hand the actual mass of liquid that is retained per impact is significantly larger for Phos-Chek XA than for the other fluids, but there would be less particle impacts (for constant dispersed retardant mass) because the drop size is larger.

3.3.2 Effect of Dowel Impact Angle

The effect of impact angle on the liquid retention efficiency was studied by positioning the 1/4 inch birch dowel at a 45° angle (with respect to the horizontal plane) as shown in Figure 2b, and discussed earlier. The results using medium sized drops and drop heights of 42 and 2 ft are shown in Table V, and compared with the normal (0°) results in Figure 7.

TABLE V. LIQUID RETAINED ON A DRY 1/4 INCH BIRCH DOWEL AFTER CENTRAL IMPACT BY A MEDIUM SIZED DROP AT A 45° ANGLE

Solution	Water	FT-931	FT-100	PC-XA
Drop Diameter, mm	4.1-4.3	4.3-4.4	4.8-4.9	4.8-5
Drop Height	42 ft			
Retained Mass, mgm	10.3	10.0	15.4	14.6
Standard Deviation	0.5(4)*	0.0(4)	1.5(5)	0.6(5)
Liquid Retention, %	28.5	22.2	24.3	23.5
Drop Height	2 ft			
Retained Mass, mgm	18.7	21.8	32.0	67.8
Standard Deviation	0.6(3)	1.2(4)	2.9(4)	11.5(4)
Liquid Retention, %	46.5	43.5	48.8	100.0

* The number in parenthesis is the number of tests.

It may be seen from Figure 7 and Table V that the general effect of increasing the impact angle is to increase the amount of liquid that is retained on the dowel, i.e., increasing impact angle increases the liquid retention efficiency. The fractional increase was not very large for the 42 ft drop heights (~ 20%) however, and was about the same for all the retardants with the possible exception of water which may have had a slightly greater value. On the other hand at the 2 ft drop height (lower impact velocity) the fractional increase of the liquid retention by increasing the impact angle from normal incidence (0°) to a 45° angle was quite large, and in the case of Phos-Chek XA allowed all of the liquid to be retained on the dowel.

3.3.3 Effect of Prewetting the Dowel

The prewetting experiments were conducted to simulate the effect of fuel wetting by previous droplet impact on the liquid retained by a succeeding impact. The experimental procedure was discussed earlier. The tests were conducted using a 1/4 inch birch dowel and the results are summarized in Table VI, and compared with the dry dowel results in Figure 8.

It may be seen from Figure 8 that at the 42 ft drop height prewetting the dowel had essentially no effect on the liquid retention, with the possible exception of water whose retention efficiency may have been slightly increased. On the other hand at the low drop height (low impact velocity), the prewetting increased the liquid retention of all the retardants significantly, with essentially all of the Phos-Chek XA being retained. As in the

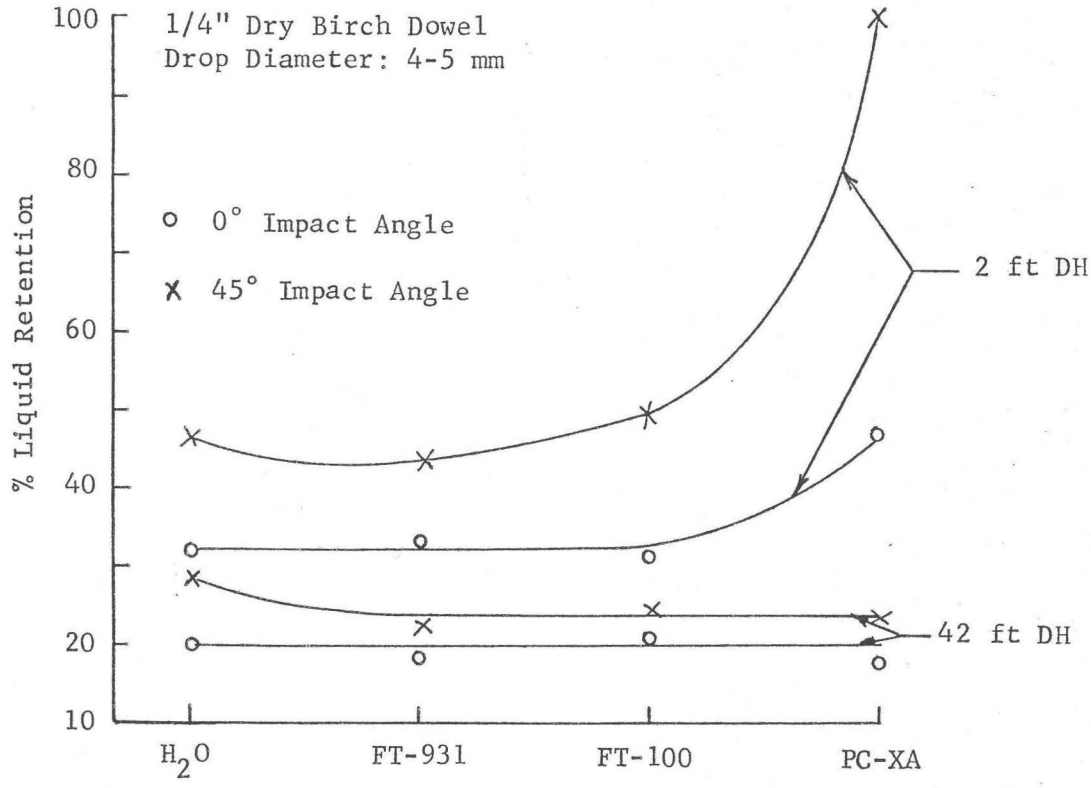


Figure 7. Comparison of the Liquid Retention at 0° and 45° Impact Angle

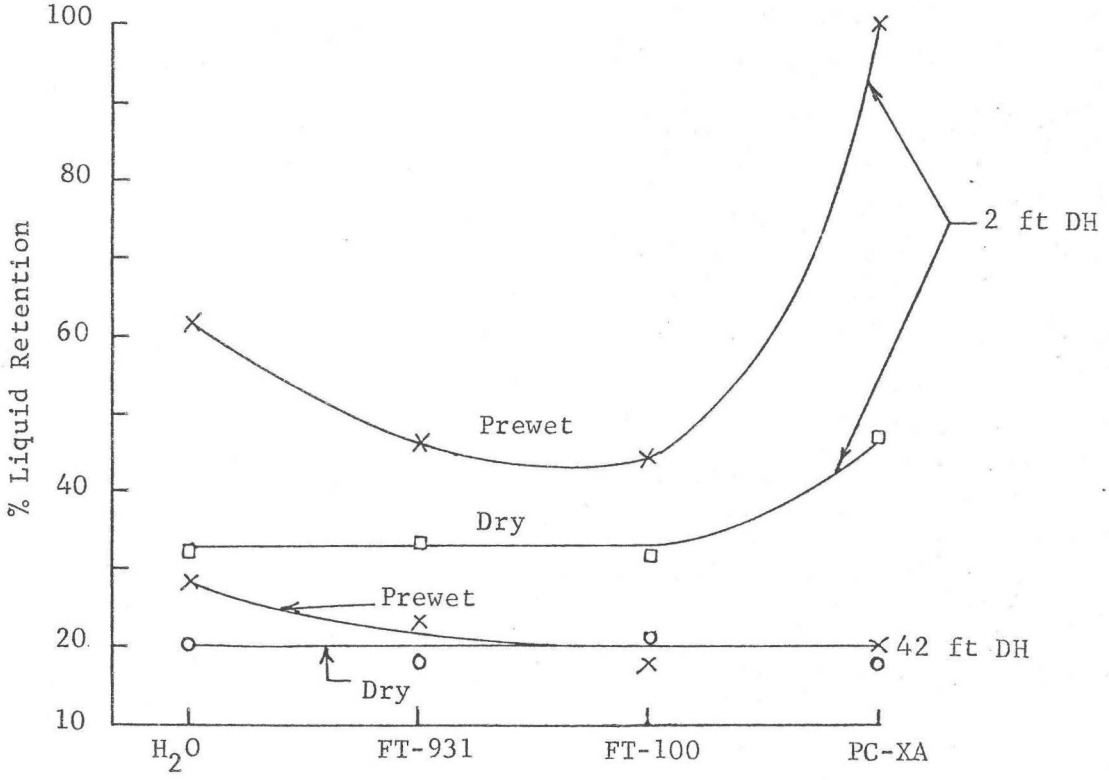


Figure 8. Comparison of the Liquid Retention on a Dry and Prewet 1/4 Inch Birch Dowel at Normal (0°) Incidence

case of the 42 ft drops, the retention of water appears to be greater than that of the two Fire-Trol solutions. The preceding results suggest that prewetting has a greater effect on enhancing the retention of liquid drip than of the rain drops during the wetting-out of a fuel.

TABLE VI. LIQUID RETAINED ON A 1/4 INCH PREWET BIRCH DOWEL AFTER CENTRAL IMPACT BY A MEDIUM SIZED DROP

Solution	Water	FT-931	FT-100	PC-XA
Drop Diameter, mm	4.2-4.3	4.4-4.5	4.8-4.9	4.9-5.0
Drop Height:	42 ft		0° Impact Angle	
Retained Mass, mgm	11.7	11.7	12.8	14.0
Standard Deviation	0.6(3*)	1.2(3)	2.6(4)	1.4(4)
Liquid Retention, %	28.1	23.0	17.8	20.2
Drop Height:	2 ft		0° Impact Angle	
Retained Mass, mgm	25.2	23.0	29.8	69
Standard Deviation	1.5(4)	1.4(2)	3.1(6)	6.4(5)
Liquid Retention, %	61.5	46.0	43.7	100.0
*The number in parenthesis indicates the number of tests.				

3.3.4 Liquid Spread Area on the Dowels

The stains left on the dowels after drop impact were roughly rectangular in shape, with some small rays occasionally emerging in both axial directions (in the 45° impacts the rays were directionalized in the direction of fluid flow). The distance around the dowel circumference on either side of the central impact point that the stain penetrated depended on the size of the drop with respect to the dowel. The stains left by the colored water and Fire-Trol 100 on the birch dowels were usually essentially uniform (Figure 9). On the other hand the stain left by Fire-Trol 931 was generally slightly nonuniform and contained some pockets. This was also true of Phos-Chek XA but to a little larger degree. The stains left on the polyethylene dowels were always nonuniform for all the retardants, and the liquid was retained on the dowel in the form of small globs and strings. However initially (immediately after drop impact) the film coverage is essentially uniform, but breaks up into fragments after standing for several seconds or more.

The rectangular arcing shape of the stains on the birch dowels made it possible to measure the spread areas produced by the impacts. Figure 10 shows these spread areas for several cases of interest .

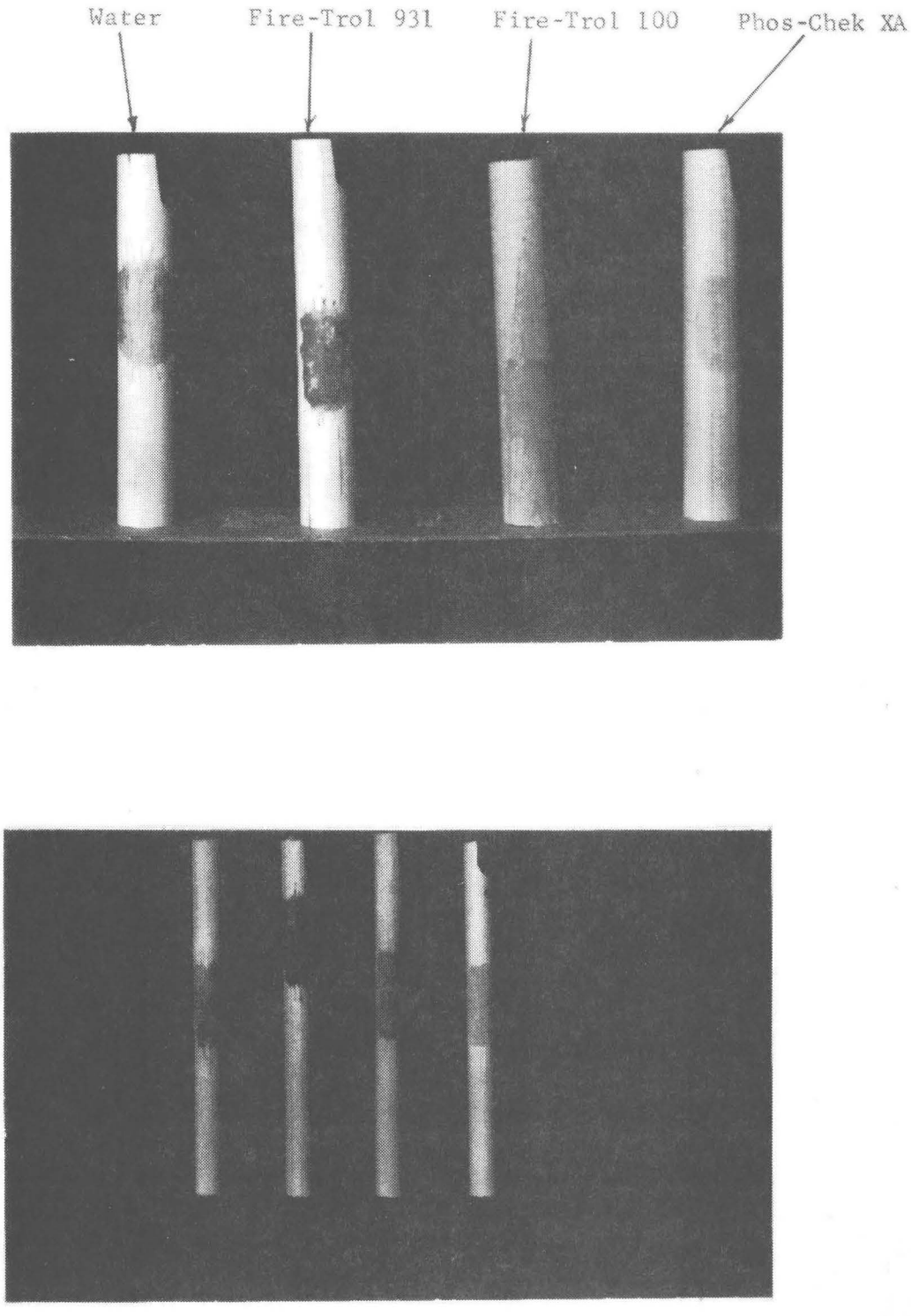


Figure 9. Dowel Stains Produced on 1/4 and 1/2 Inch Birch Dowels by Medium Sized Drops. (Drop Height = 42 ft).

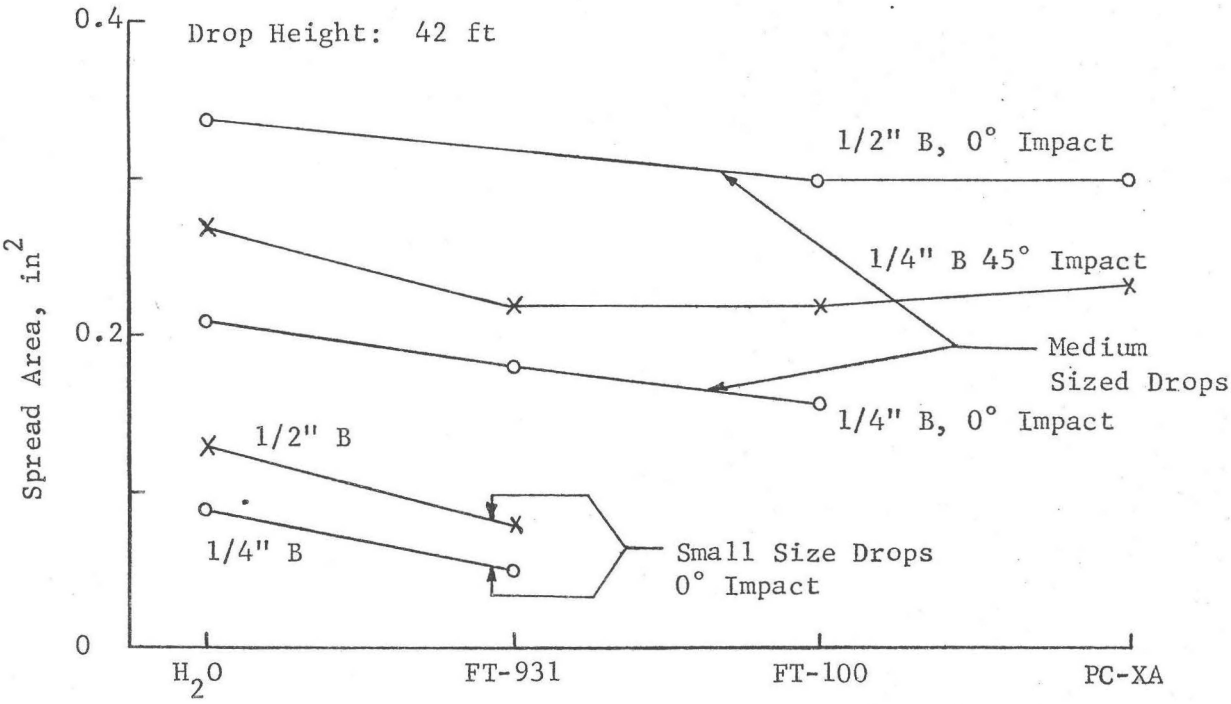


Figure 10. Spread Area of the Retardants on the Dry Birch (B) Dowels After Impact

It is seen that the spread area is larger for larger drop size, dowel size and impact angle. Using the spread areas in this figure and the corresponding measured values of the liquid retained on the dowel allows estimates to be made of the average film thickness produced by the impacts. For example, the estimated film thicknesses produced by medium sized drops impacting at 0° on a 1/2 inch birch dowel are: Water, $2.73(10^{-3})$ inch; FT-931, $3.11(10^{-3})$ inch; FT-100, $4.75(10^{-3})$ inch and PC-XA, $3.97(10^{-3})$ inch.

3.3.5 High Speed Photographic Studies

As discussed earlier, high speed photographs of the drop impacting with the dowels were taken in selected cases to help provide information regarding the impaction process. The experimental setup was discussed in Section 3.2.3.

In ref. 5, high speed photographs were given of a medium sized (4-5 mm) drop of Phos-Chek XA impacting centrally (after a 40 ft fall) on a 1/8-inch diameter birch dowel, and a drop of Fire-Trol 100 impacting on a 1/4-inch diameter dowel. It was found that the liquid initially tended to spread and flow laterally off both sides of the dowel in the form of a sheet. In the case of the Phos-Chek the sheet narrowed (necked) as the flow continued and ultimately became a ligament near the end of the event. This necking behavior was believed to be due to the elastic nature of the flowing liquid. On the other hand, although the initial phase of the spreading for Fire-Trol 100 (which is shear thinning and nonelastic) was similar to that of Phos-Chek, it differed in the latter stages in that the sheet maintained essentially its full width during the flow process, and then suddenly fractured along its entire width near the dowel. There was no evidence of liquid wrapping around the dowel during the impaction process for either fluid.

3.3.5.1 High Drop Height Tests

In the present program some early photographic studies were made of medium size drops impacting with a dowel after a 42 ft drop. Only off-center (non-central) impacts on the dowels were obtained in these tests, and one mirror was used so that only two views of the event were obtained. In one test shown in Figure 11, Phos-Chek XA was dropped on a 1/2 inch diameter polyethylene dowel. In this case the flow and subsequent necking fracture behavior of the liquid is the same as was observed in ref. 5, but the flow is not axially symmetrical. In several other tests Fire-Trol 931 was dropped on a 1/2 inch birch dowel. In these cases the flowing liquid sheet appeared to narrow slightly, and then fractured quickly in a manner similar to Fire-Trol 100 in ref. 5. These photographs were not suitable for duplication and are therefore not given here.

It may be seen in the pictures of Figure 11 that some liquid is initially present on the back lateral half of the dowel before the impact of the falling drop, which took place on the front lateral half of the dowel. This liquid was produced by an earlier impact of a drop of Phos-Chek XA which was not photographed. The liquid did not interfere with or affect the impact behavior of the drop given in Figure 11. It is however a good illustration of the general nature and form of the liquid that was retained on the polyethylene dowels after impact by the various retardants. The stringiness and localized area concentrations of the liquid can be compared with the relatively uniform stains produced on the birch dowel that are shown in Figure 9.

3.3.5.2 Low Drop Height Tests

Because most of the rheological effects in the liquid retention studies were observed at a low ($\sim$ 2 ft) drop height (hence low impact velocity), many of the photographic studies were also made at approximately this same height. As discussed before, the liquid retention of a medium sized drop of Phos-Chek XA impacting with a dowel after a 2 ft fall is significantly larger than for the other fluids, which were approximately the same. Figure 12 shows a few selected frames of a medium sized Phos-Chek XA droplet impacting on a 1/2 inch dry birch dowel after a drop of about 2-1/4 ft (giving an impact velocity of about 12 ft/sec). Two mirrors were used in photographing the impact and each picture gives the front, the top and the side view of the event. It may be seen that after impacting, the Phos-Chek XA drop flattens, and then flows laterally off the dowel in both directions in the form of a sheet. During the flowing the liquid elongates but does not fracture, and the side view shows that it does not wrap around the dowel. In the latter stages of the event, a maximum elongation is reached and the opposing ends are then pulled back towards the center of the dowel (the liquid narrows into a ligament during the pullback). This phenomenon can be better observed in Figure 13, which shows blowups of the corresponding sideviews of the event.

From the preceding pictures then it can be seen that the large (essentially 100%) retention of the Phos-Chek XA on the dowel after a low drop height (hence low impact velocity) impact is due to the fact that the initially-flowing liquid does not fracture, and is subsequently pulled back on the dowel by the elastic nature of the flowing liquid.

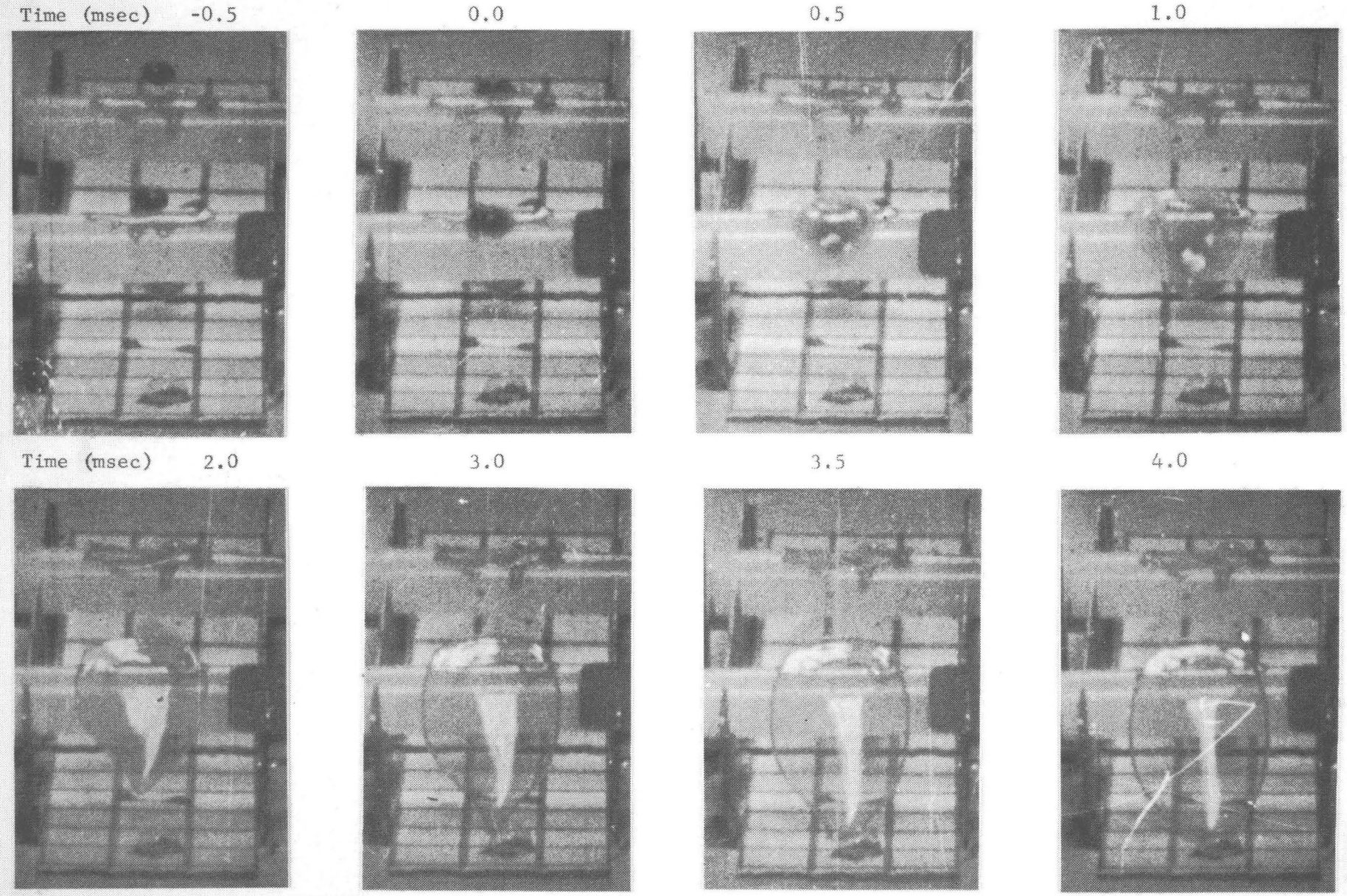


Figure 11. Selected Frames From the Impact of a Falling Drop (4.7 mm) of Phos-Chek XA With a 1/2 Inch Polyethylene Dowel. $V_i \simeq 26.5$ ft/sec.

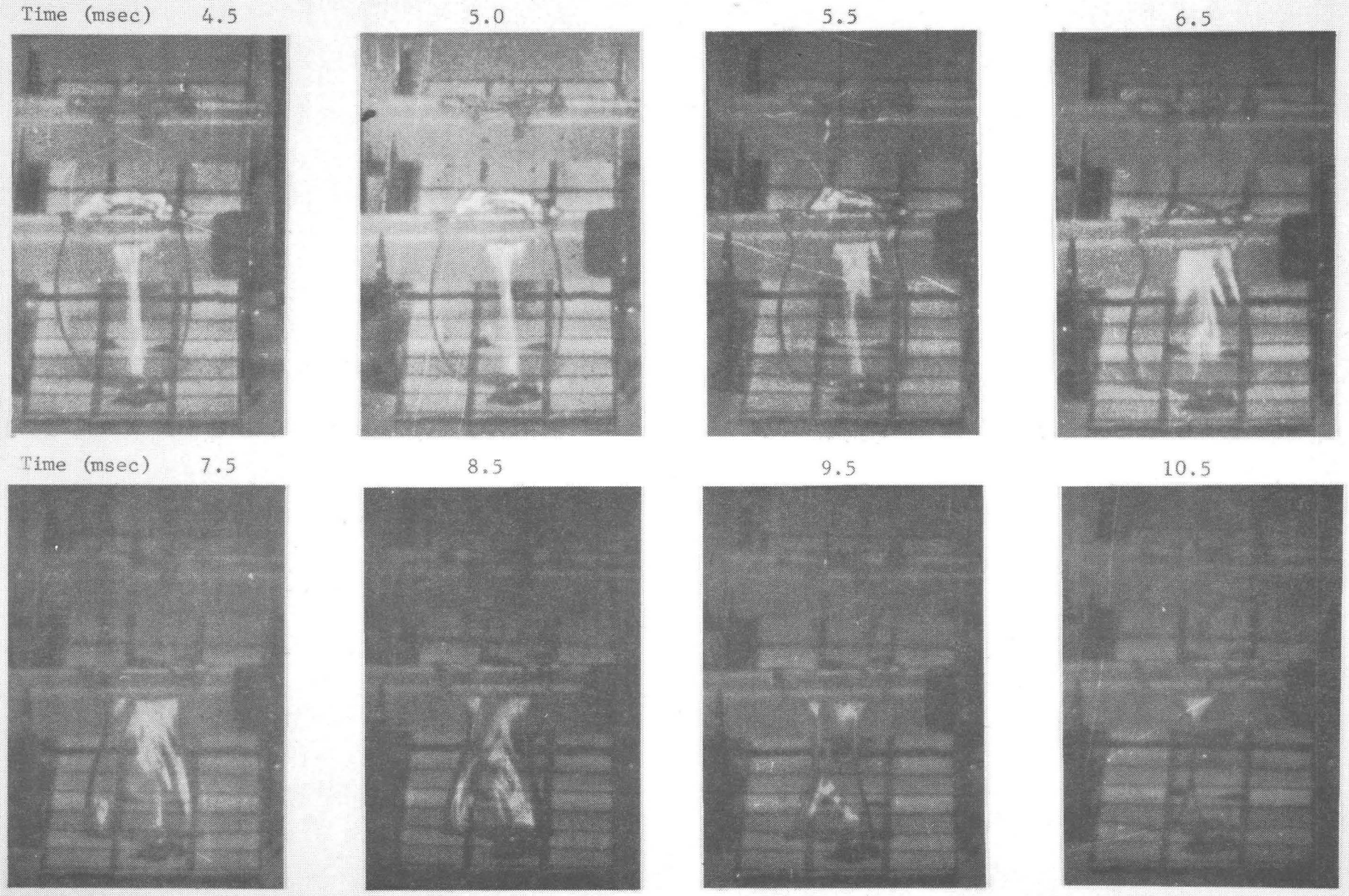


Figure 11. (Concluded) Selected Frames From the Impact of a Falling Drop (4.7 mm) of Phos-Chek XA With a 1/2 Inch Polyethylene Dowel. $V_i \simeq 26.5$ ft/sec.

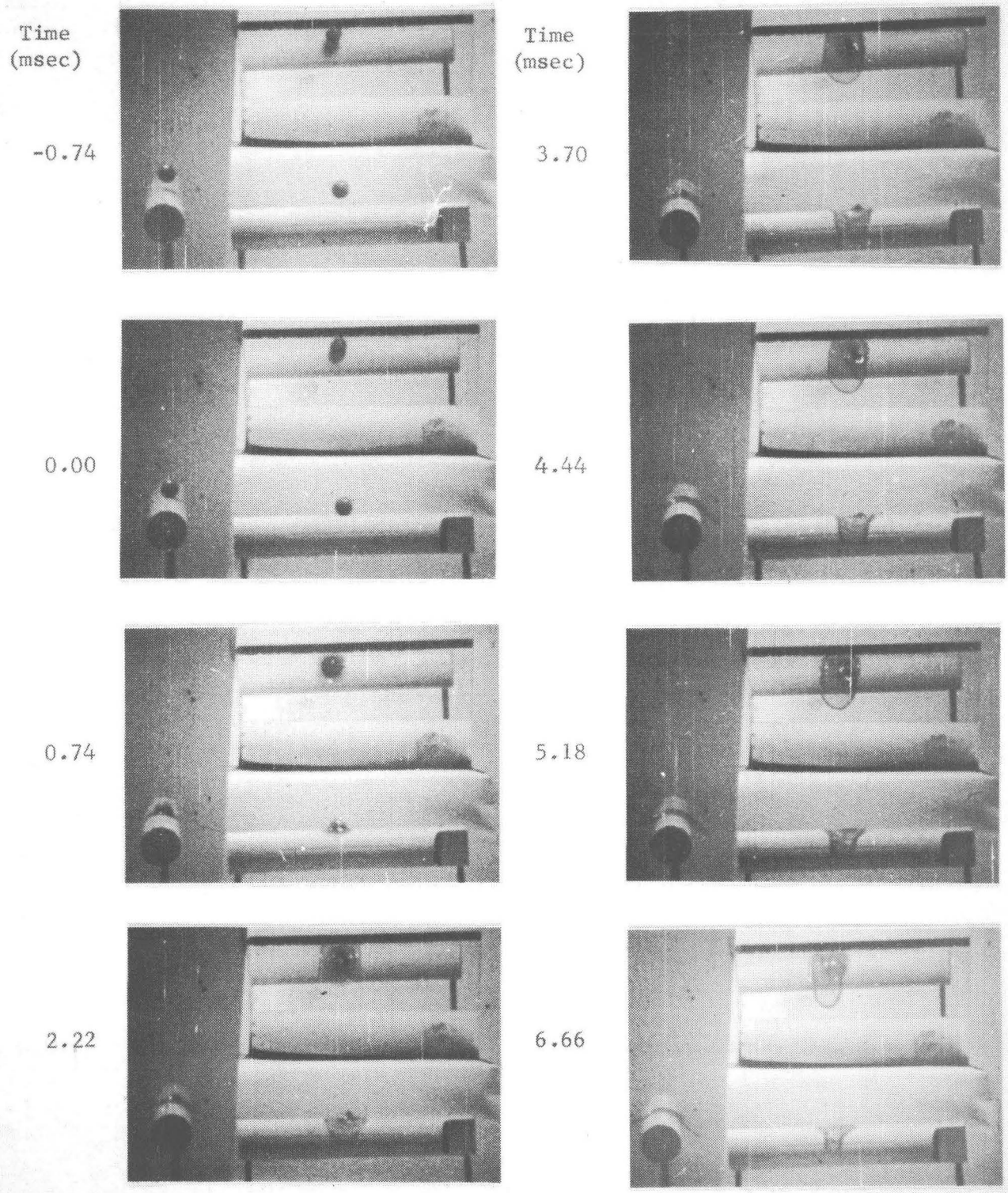


Figure 12. Selected Frames From the Impact of a Falling Drop (4.88 mm diam.) of Phos Chek XA With a 1/2 Inch Birch Dowel, V_i = 12.0 ft/sec.

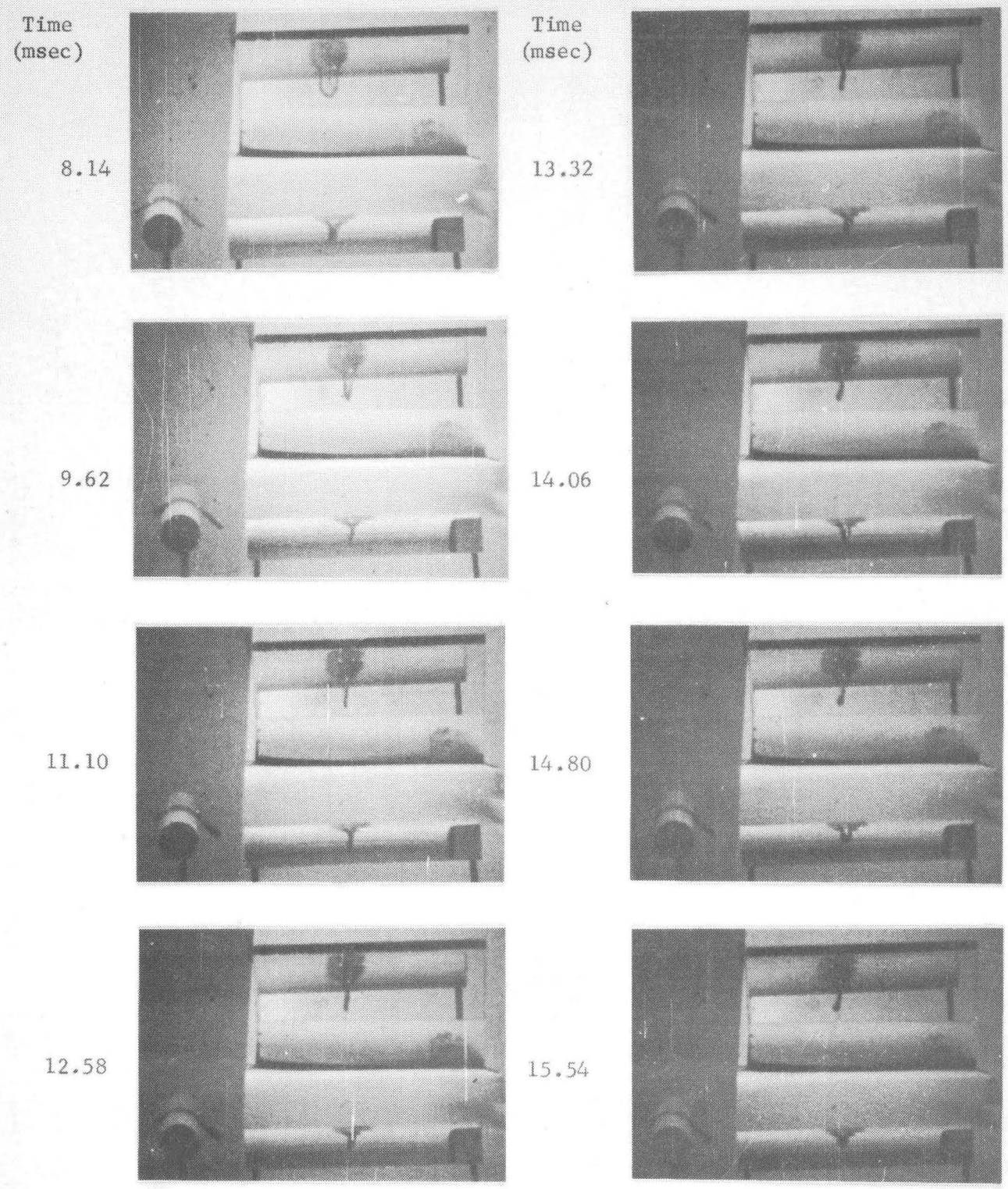


Figure 12. (Concluded).

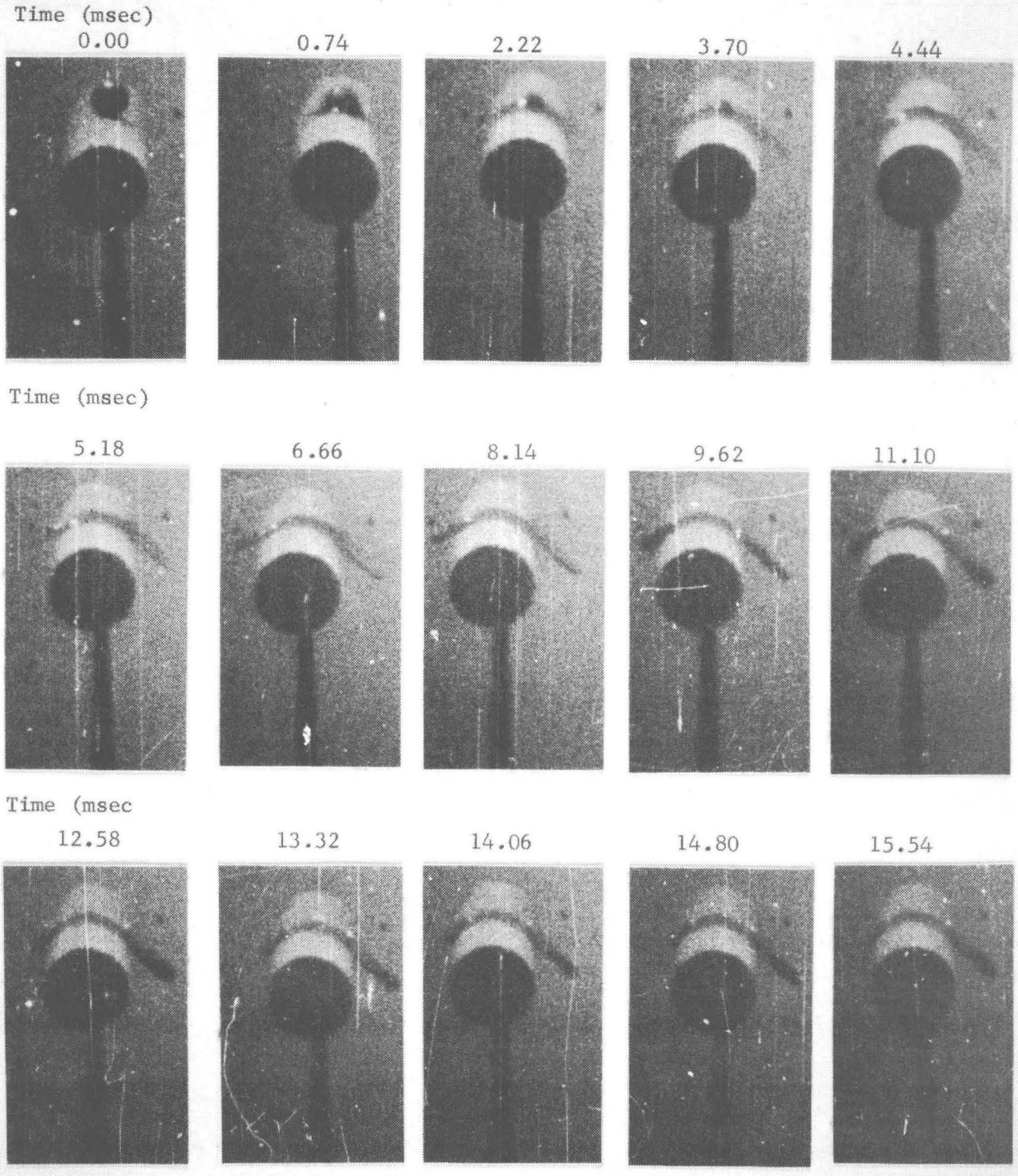


Figure 13. Blowups of the Side View Pictures of Figure 12.

On the other hand, high speed photographs of the impact of a drop of Fire-Trol 100 (Figure 14) and Fire-Trol 931 (Figure 15) impacting on a similar dowel at the same impact velocity show that in these cases after the impact the liquid initially flows and spreads in a similar manner to Phos-Chek, but subsequently fractures and sprays off the dowel. This results in a lower percentage of liquid being retained on the dowel, as was observed in the weighing experiments. Comparing the sideviews of Figure 13 with those of Figure 14 and Figure 15, it is observed that the Phos-Chek XA drop spreads and elongates at a larger angle from the top of the dowel than do the drops from the two Fire-Trol solutions.

3.3.5.3 Retention Efficiency vs Fuel Composition

From the results of Table II, it can be seen that the percent retention of water and the two Fire-Trol solutions on a 1/2 inch polyethylene dowel at 0° impact angle and a 2 ft drop height is significantly larger than it is on a 1/2 inch birch dowel. The retention of the Phos-Chek XA is about the same on both dowels and is near 100% (i.e., essentially all of the drop). It was seen in Figures 12 and 13 that the large retention efficiency of Phos-Chek XA on birch at low drop height is due to the fact that the initially-flowing liquid does not fracture, and is subsequently pulled back on the dowel by the elasticity of the liquid.

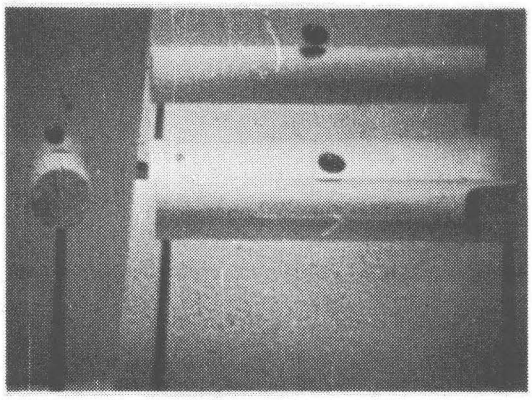
In order to obtain further information regarding the differences of the effect of dowel compostion on the retention efficiency of the other liquids, a photographic sequence was taken of the impact of a drop of Fire-Trol 100 impacting with a 1/2 inch polyethylene dowel. Selected frames are shown in Figures 16 and 17. It is seen in this case that as the drop impacts and flattens out, the flowing liquid wraps around the dowel, which increases its retention efficiency. This was the first evidence of liquid wrap-around during impact that was observed, although it has often been speculated on - particularly for an elastic liquid (Fire-Trol 100 is a nonelastic liquid). Interestingly enough, the wrap-around was not observed for the impact of Phos-Chek XA with the polyethylene dowel, as may be seen in Figures 18 and 19, but was observed for Fire-Trol 931 as seen in Figure 20 and also in two other films (including Figure 21) in which the impact was off-center. It would thus appear that the retention efficiency of polyethylene is larger than that of birch because its composition or surface properties in some manner causes the impacting drop to come in contact with a larger surface area of the dowel, and this hypothesis is supported by the splatter patterns (to be discussed).

3.3.5.4 Effect of Surface Roughness

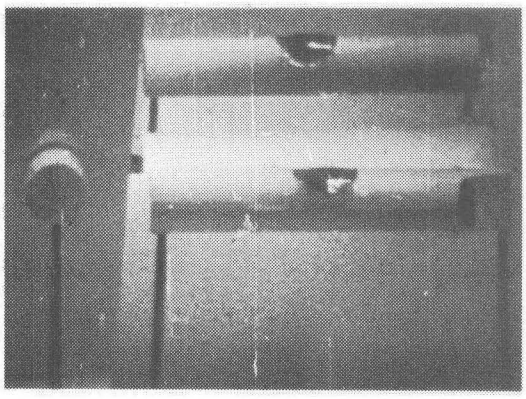
Based on the preceding results and other studies (to be discussed) it would appear that it is surface roughness rather than fuel composition per se that causes the liquid retention to be greater on polyethylene than on birch. Thus the observed lateral flowing (circular jetting) of the various impacting liquids off the sides of the birch dowels is apparently due in part to the natural surface roughness of the dowel material, which in the case of Fire-Trol 100, Fire-Trol 931 and water allows a certain fraction of the liquid to escape dowel retention. On the other hand, the smooth surface of polyethylene allows these three (essentially) nonelastic and low viscosity (the Fire-Trols undergo shear thinning) liquids to wrap around the polyethylene dowel

Time (msec)

-0.54

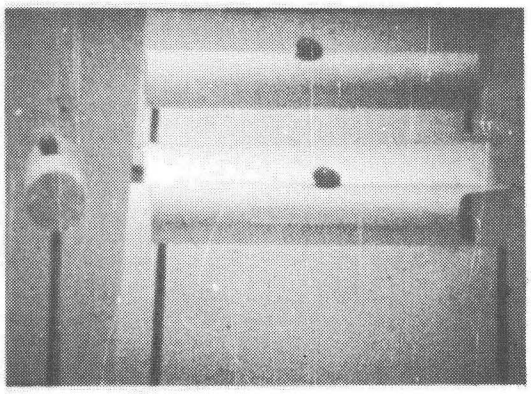


1.62

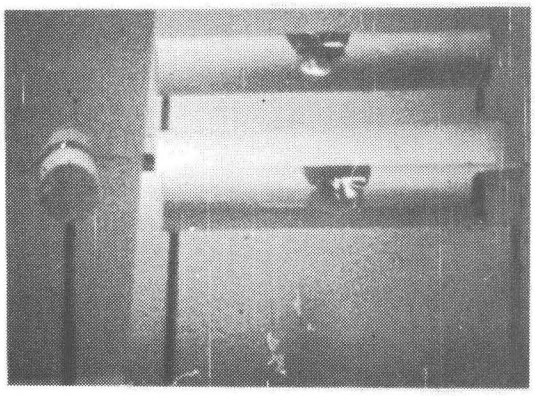


Time (msec)

0.00

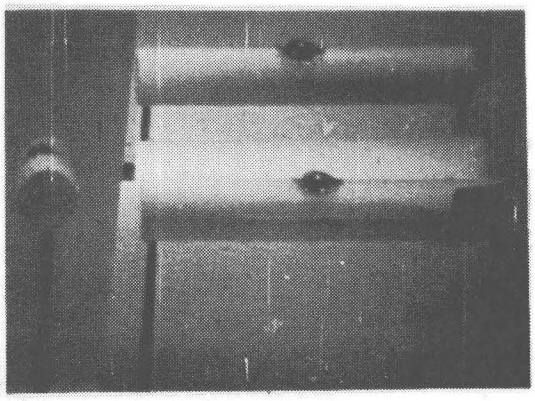


2.70



Time (msec)

0.54



3.78

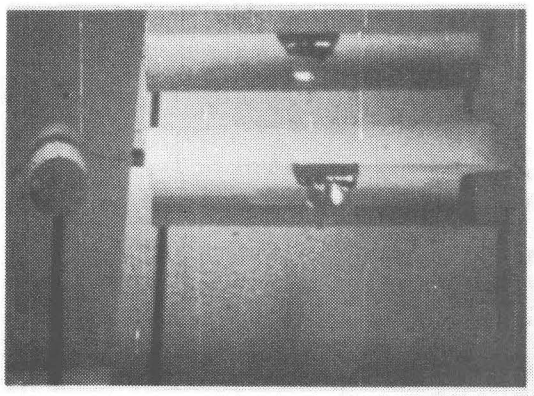
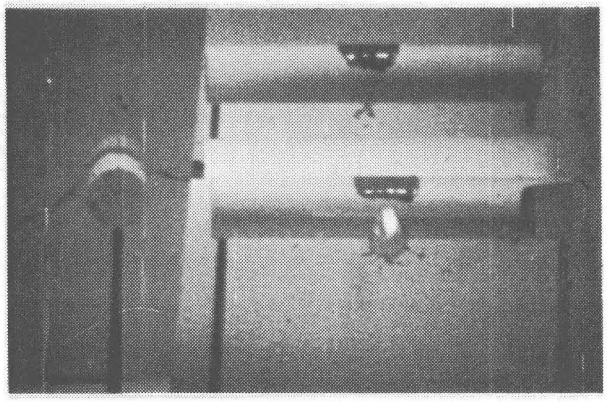


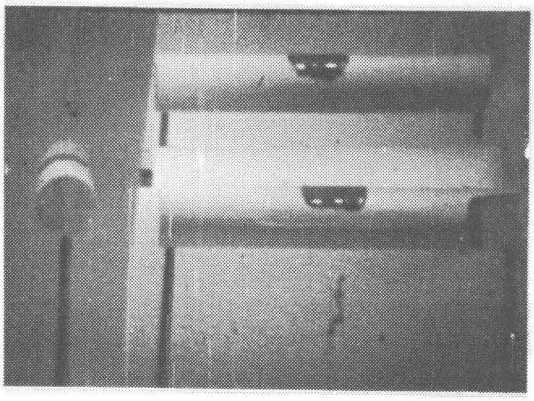
Figure 14. Selected Frames From the Impact of a Falling Drop (4.9 mm diam.) of Fire-Trol 100 With a 1/2 Inch Birch Dowel, V_i = 12 ft/sec.

Time (msec)

5.94

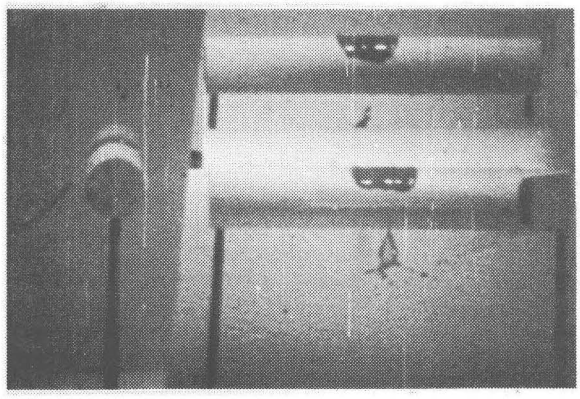


11.34

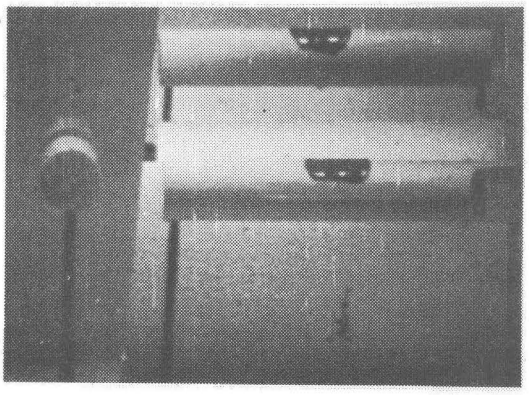


Time (msec)

8.10

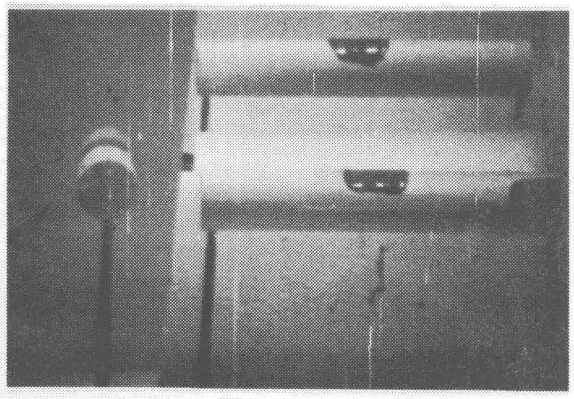


14.58



Time (msec)

10.26



19.98

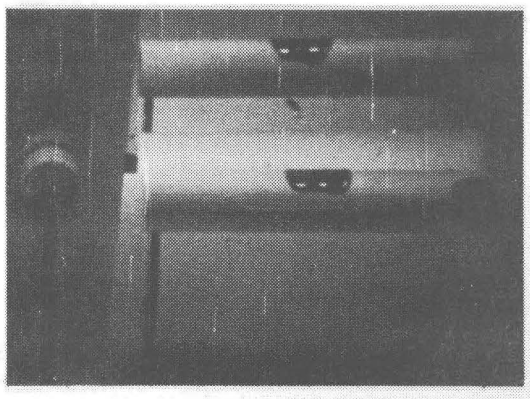


Figure 14. (Concluded).

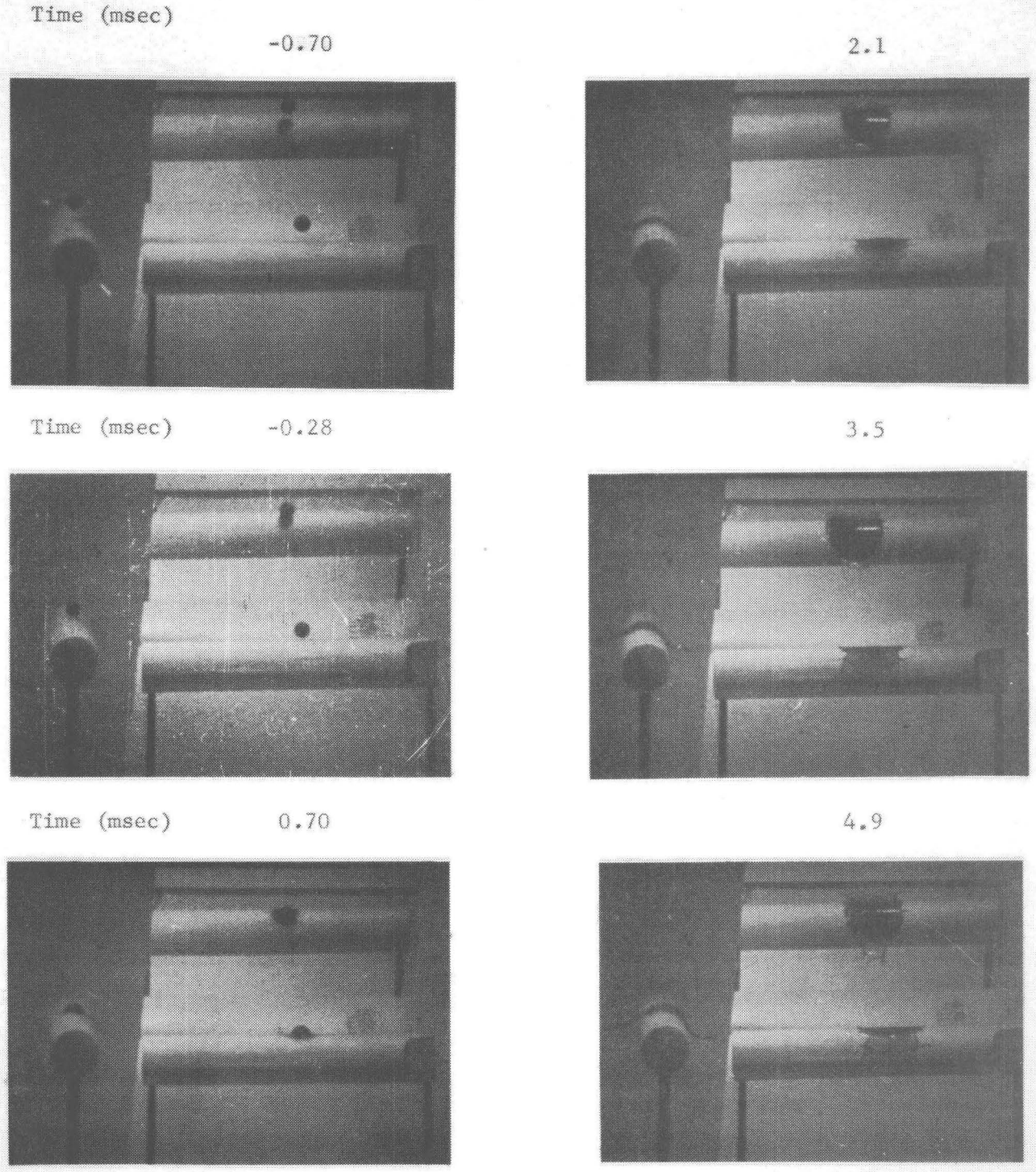
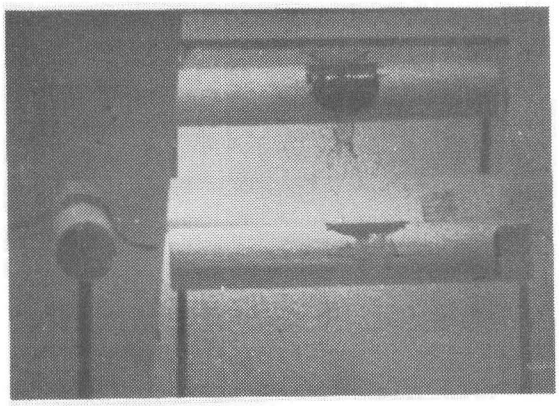


Figure 15. Selected Frames from the Impact of a Falling Drop (4.5 mm diam.) of Fire-Trol 931 With a 1/2 Inch Birch Dowel, V_i = 12 ft/sec.

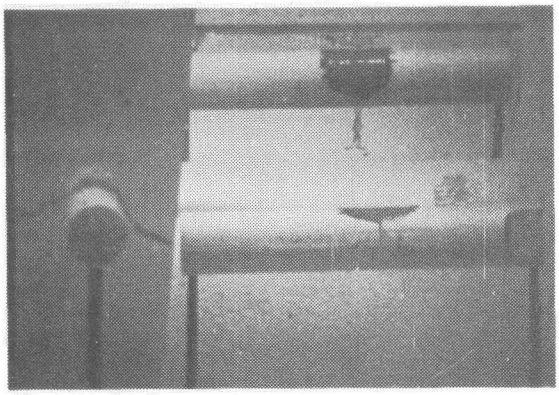
Time (msec)

6.3



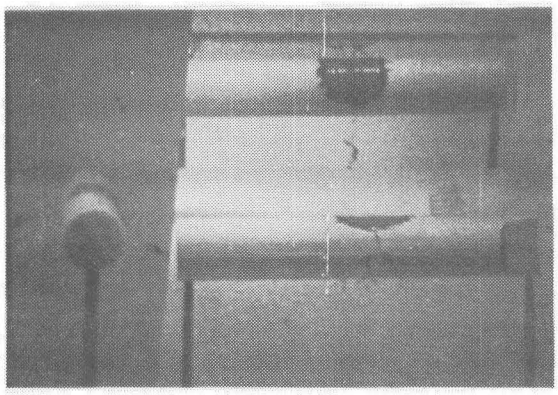
Time (msec)

7.7

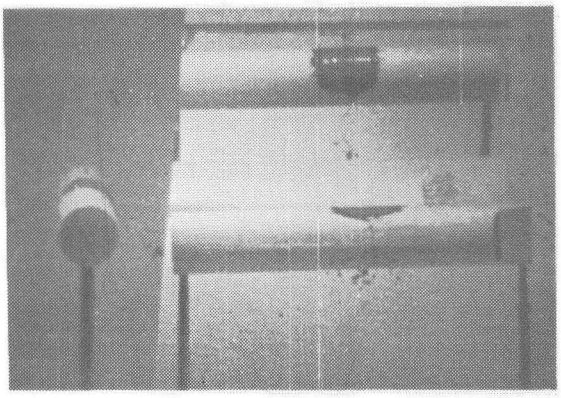


Time (msec)

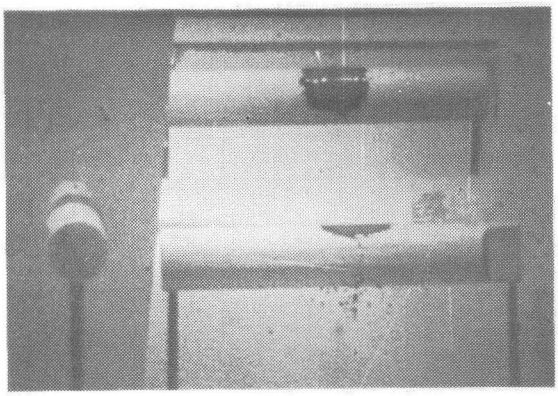
9.1



10.5



11.9



13.3

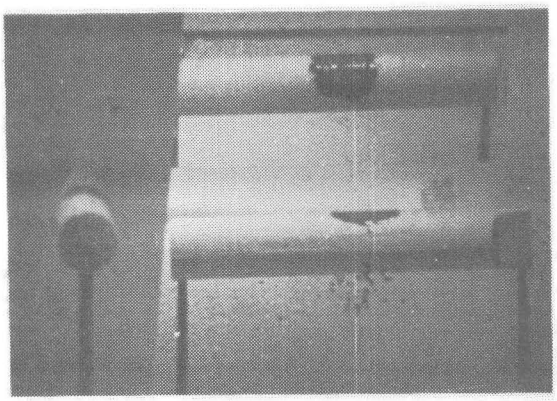


Figure 15. (Concluded).

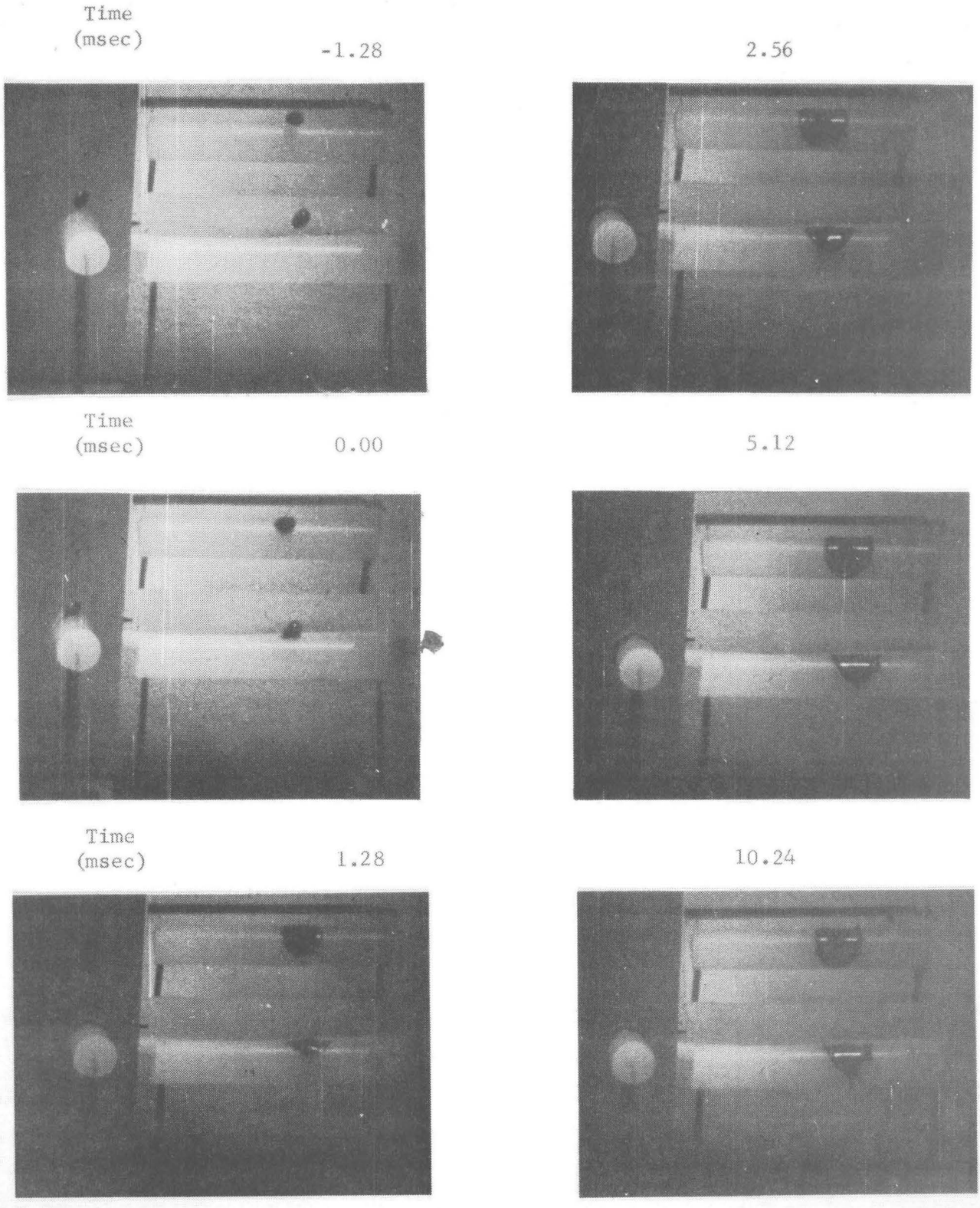
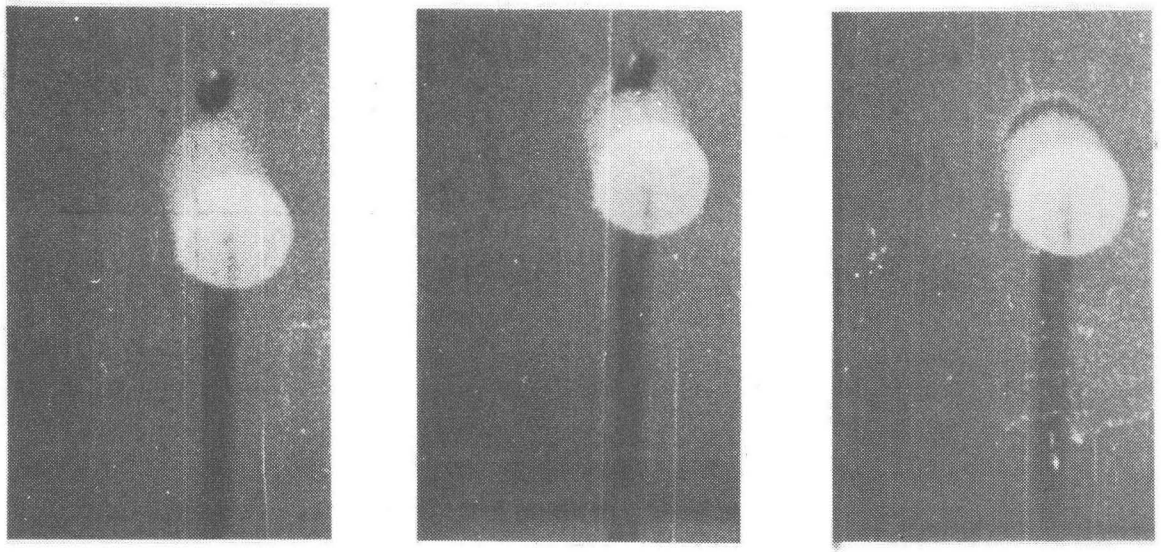


Figure 16. Selected Frames from the Impact of a Falling Drop (4.9 mm diam.) of Fire-Trol 100 with a 1/2 Inch Polyethylene Dowel, V_i = 12 ft/sec.

Time (msec)

-1.28 0 +1.28



Time (msec)

2.56 5.12 10.24

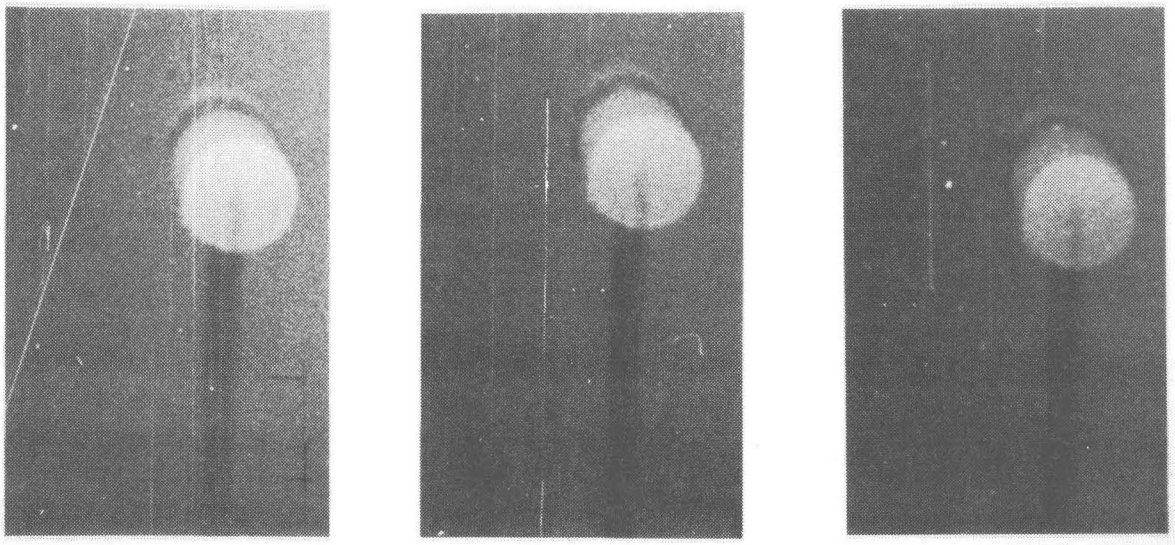


Figure 17. Blowups of the Side View Pictures of Figure 16.

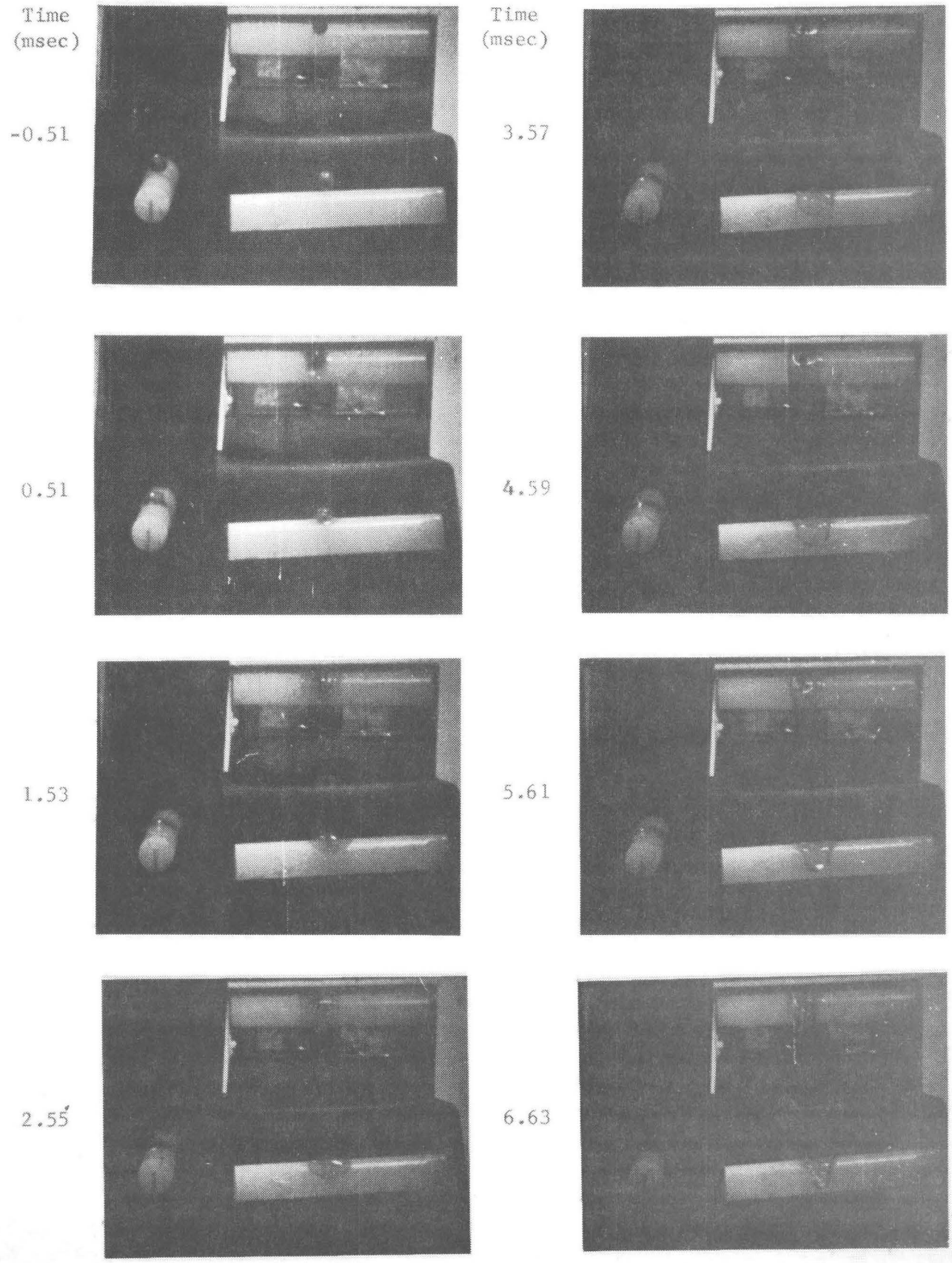


Figure 18. Selected Frames From the Impact of a Falling Drop (4.8 mm diam.) of Phos-Chek XA with a 1/2 Inch Polyethylene Dowel, V_i = 12 ft/sec.

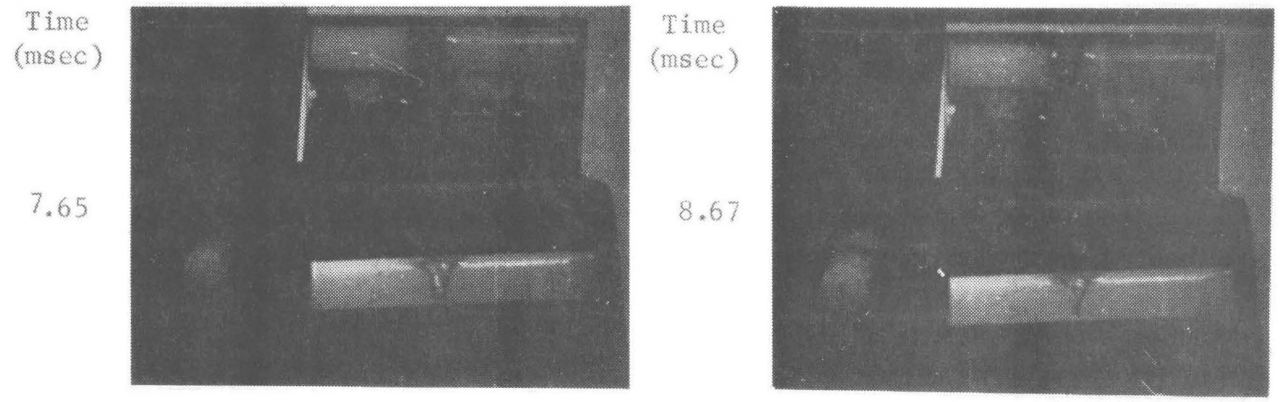


Figure 18. (Concluded).

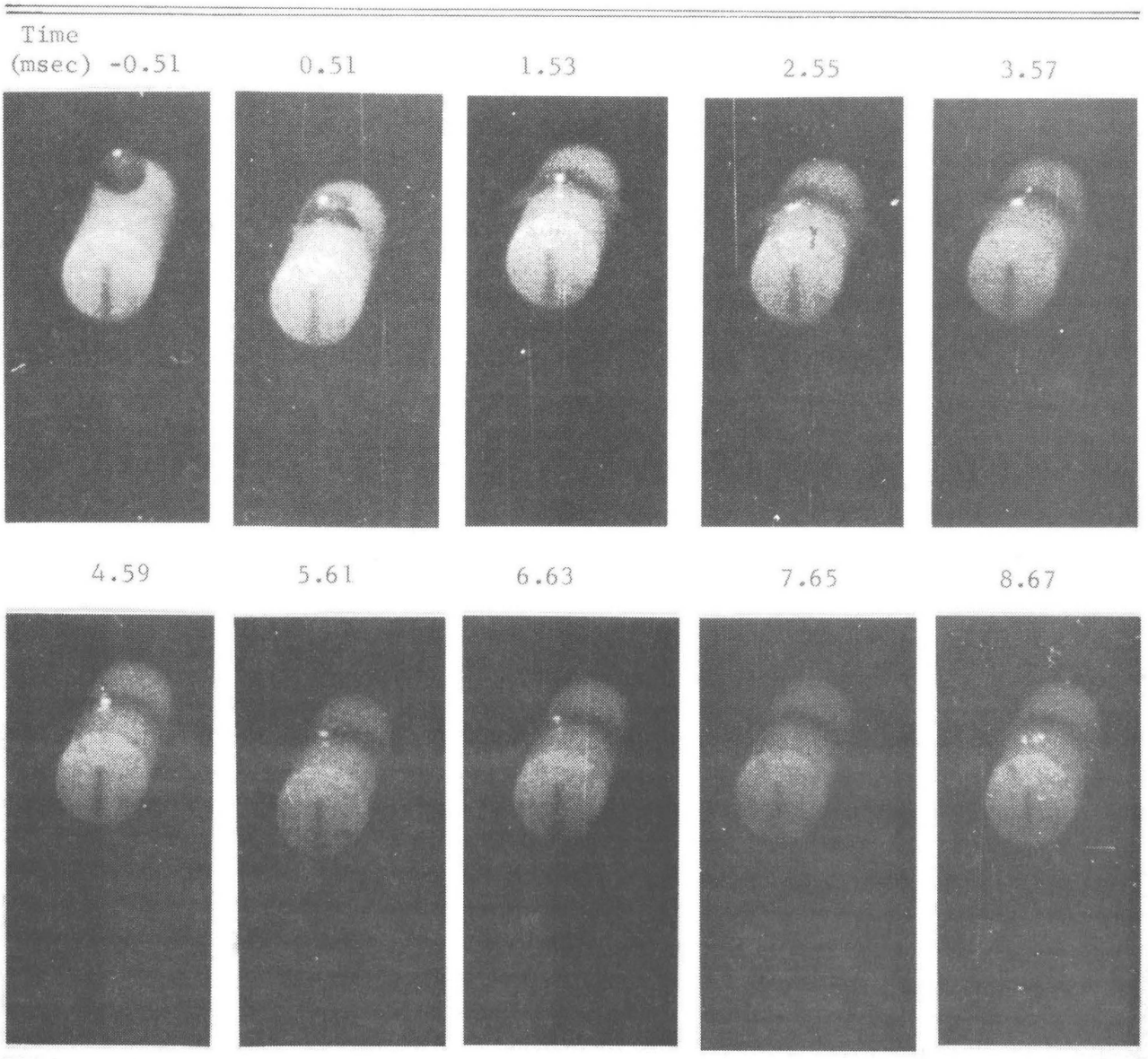
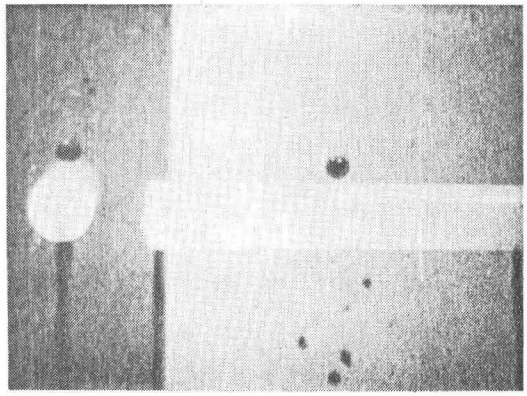
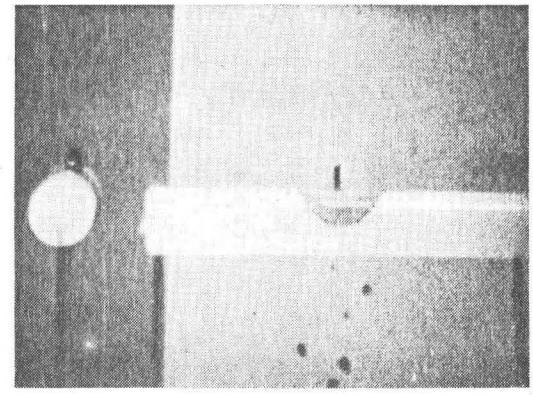


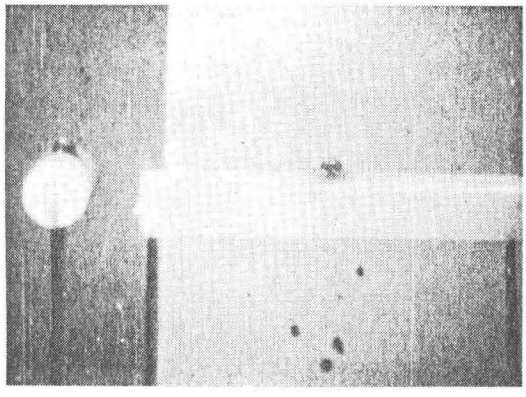
Figure 19. Blowups of the Side View Pictures of Figure 18.



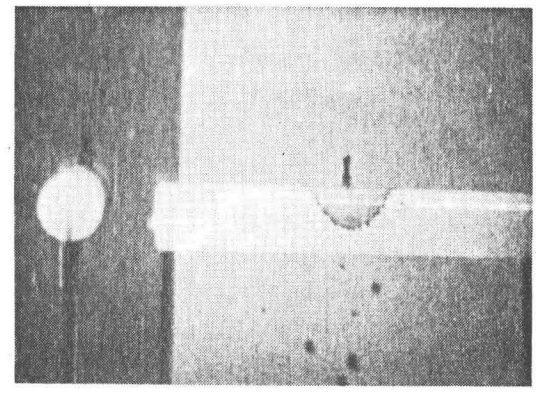
-0.16 msec



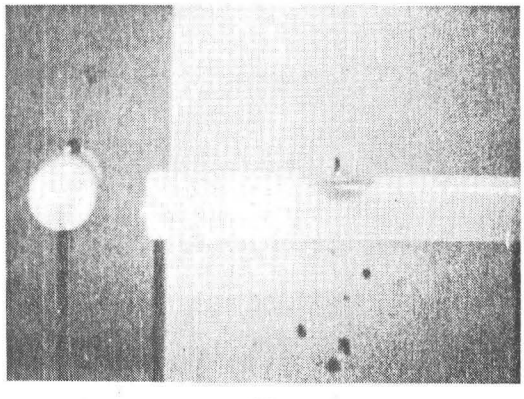
3.44 msec



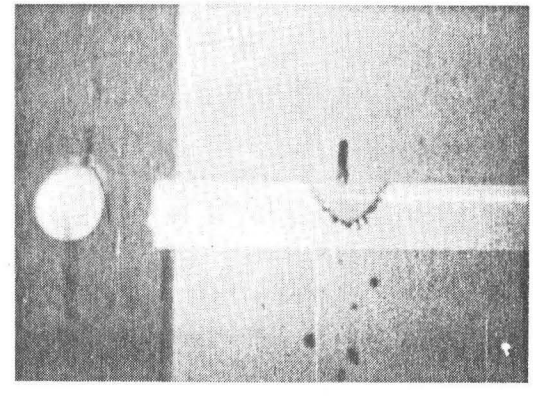
1.04 msec



4.64 msec



2.24 msec



7.04 msec

Figure 20. Selected Frames from the Impact of a Falling Drop of Fire-Trol 931 (4.5 mm dia.) With a ½ Inch Polyethylene Dowel, V_i=12 ft/sec.

(streamline flow) and thus expose a larger fraction of the liquid to the dowel, which results in a greater retention. In the case of Phos-Chek the relatively large elastic forces prevents the flowing liquid from following the surface contour of the underside of the polyethylene dowel, which results in the lateral jetting of the liquid as in the case of the birch dowel. However in these cases (both composition dowels), essentially all of the Phos-Chek is retained on the dowel due to the subsequent pull-back of the flowing liquid by the fluid elasticity.*

3.3.5.5 Vertical Impact Jetting

Figure 20 illustrates an interesting phenomenon that was occationally observed during the impact of Fire-Trol 931 with polyethylene, viz, the formation of a vertical jet. This jet is also present in Figure 21, which illustrates an off-center impact. The significance of the vertical jet is not known, but is probably related to the properties of the liquid since it has been observed before during the impact of Fire-Trol 931 with a wood target. The presence of instability growth can also be seen at the periphery of the advancing fluid flow on the dowel.

3.3.5.6 Effect of Dowel Impact Angle

Figure 22 shows a drop of Phos-Chek XA (2 ft drop height) impacting with a 1/2 inch birch dowel at a 45° angle. The flow becomes directionalized in the dowel axis direction, and the liquid remains largely on the top surface of the dowel. The impact characteristics of Phos-Chek on a polyethylene dowel are about the same (Figure 23). Fire-Trol 931 differs slightly in that there is more wrap around of the dowel by the liquid (Figure 23) although in this case the impact was slightly off center.

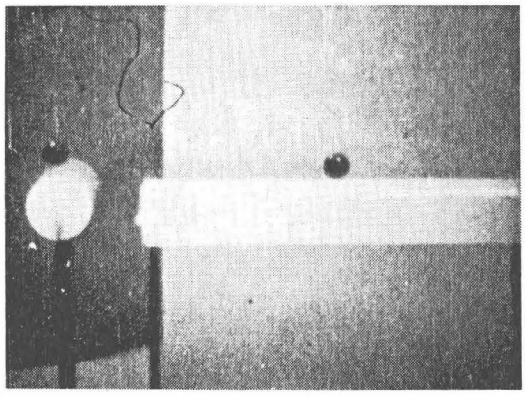
3.3.6 Discussion of the Splatter Patterns

As discussed in Section 3.2.2, an impactor card was placed centrally below the dowel in the various impact tests to obtain information regarding the splatter pattern of the liquid produced by drop impact with the dowel and the effects of the various parameters.

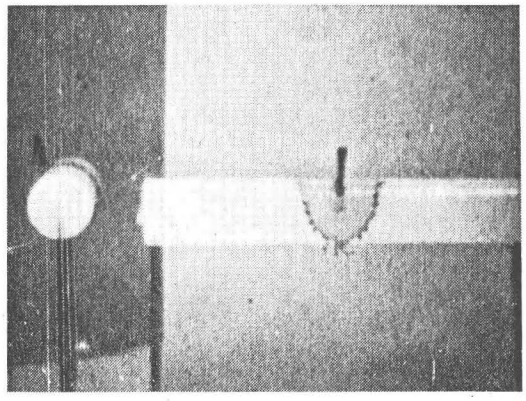
3.3.6.1 Off-Center Versus Central Impact

The central impact of a drop on a dowel results in an essentially symmetric splatter pattern of liquid being produced on both sides of the dowel, whereas an off-center impact produces an unsymmetric pattern. The general characteristics of the liquid splatter and its pattern depend both on the properties of the liquid and the impact position on the dowel.

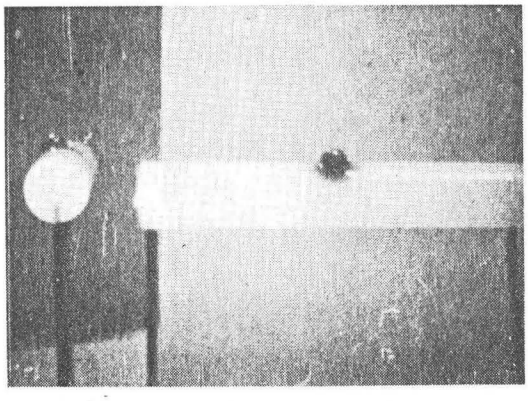
* At large drop heights the retention of Phos-Chek XA (as well as the other fluids) on polyethylene is greater than on birch because of the greater longitudinal spreading of the impacting liquid.



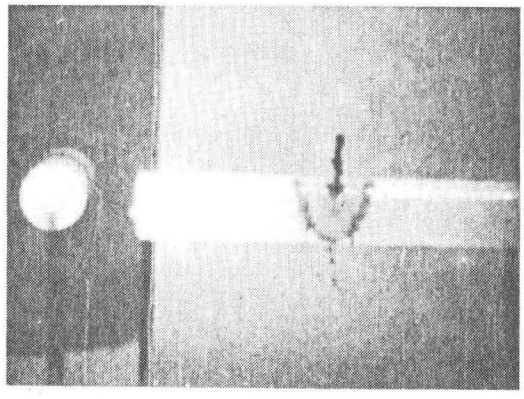
0 msec



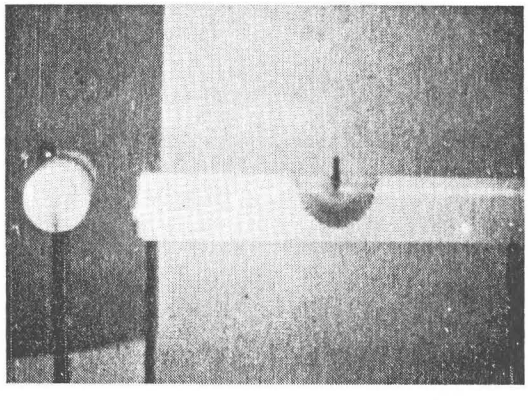
6.30 msec



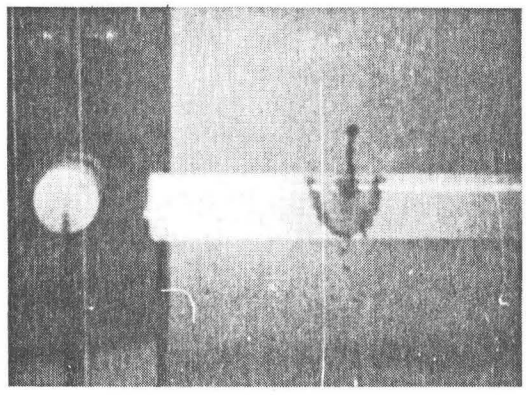
1.05 msec



10.50 msec

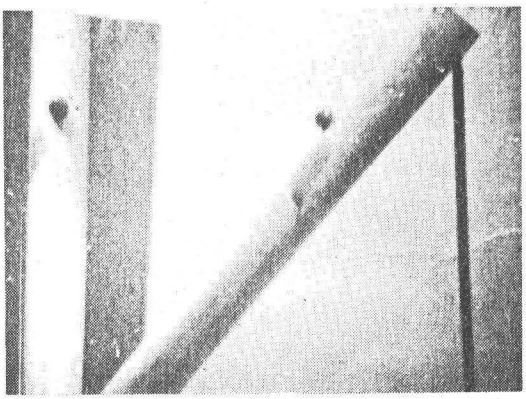


3.15 msec

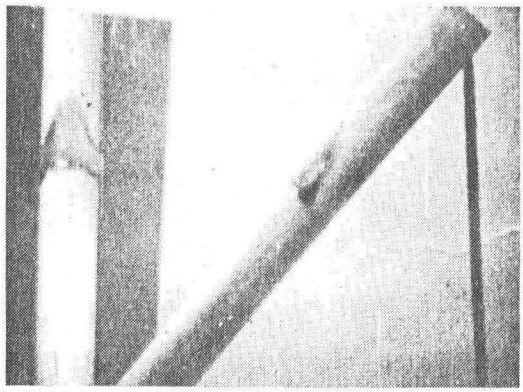


14.7 msec

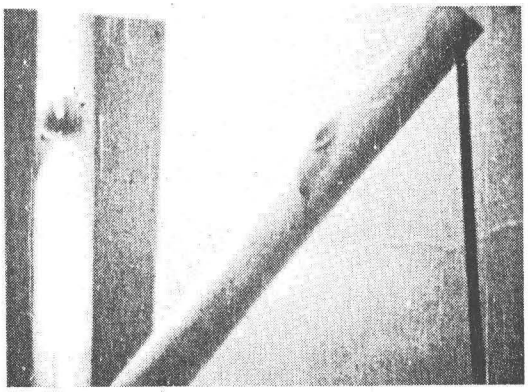
Figure 21. Selected Frames from the Off-Center Impact of a Falling Drop of Fire-Trol 931 With a ½ Inch Polyethylene Dowel, V_i=12 ft/sec.



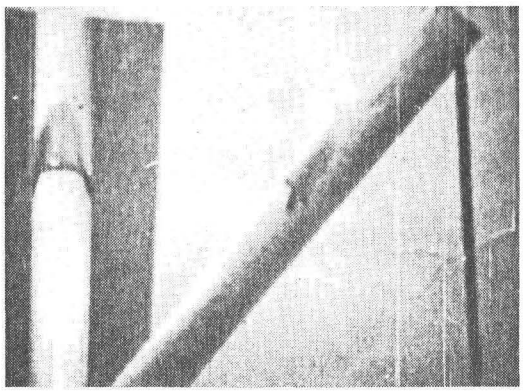
0 msec



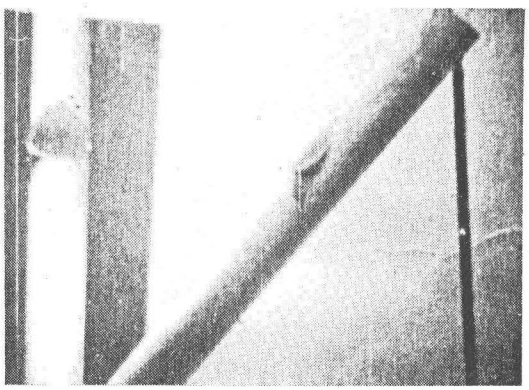
6.36 msec



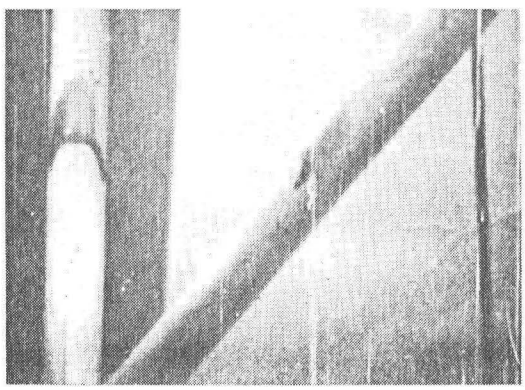
1.59 msec



9.54 msec



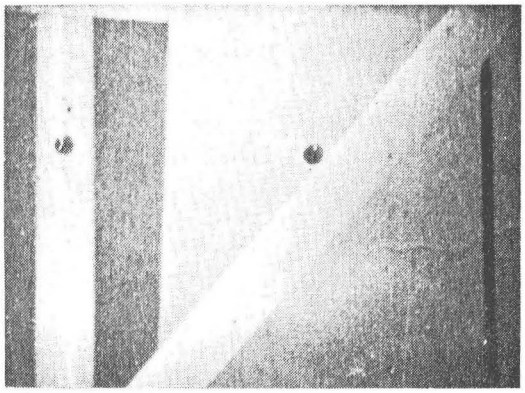
3.18 msec



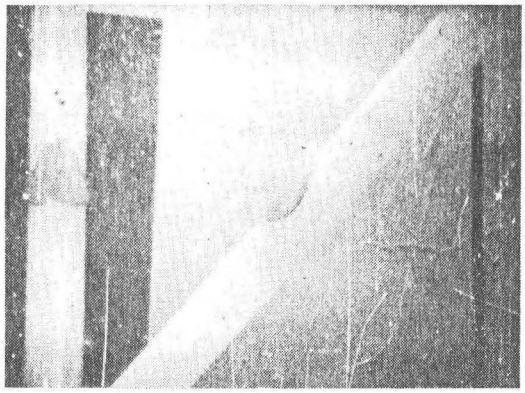
12.72 msec

Figure 22. Selected Frames from the Impact of a Falling Drop of Phos-Chek XA (4.9 mm dia.) With a ½ Inch Birch Dowel at 45°, V_i=12 ft/sec.

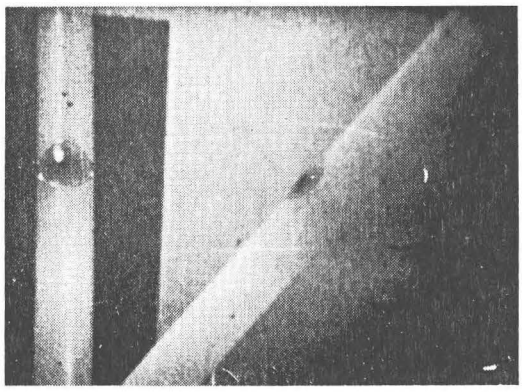
Phos-Check XA



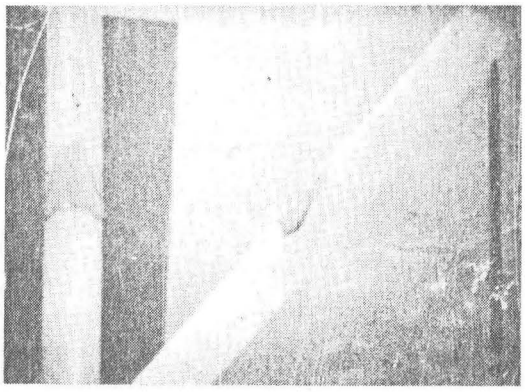
0 msec



4.68 msec

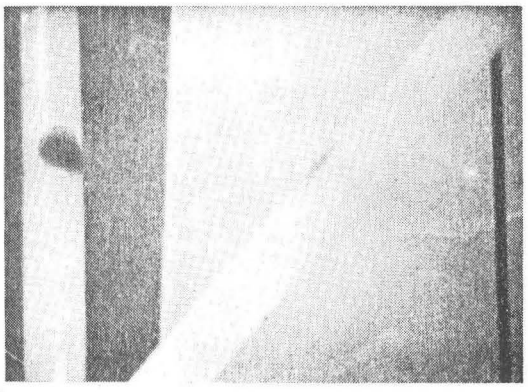


2.34 msec

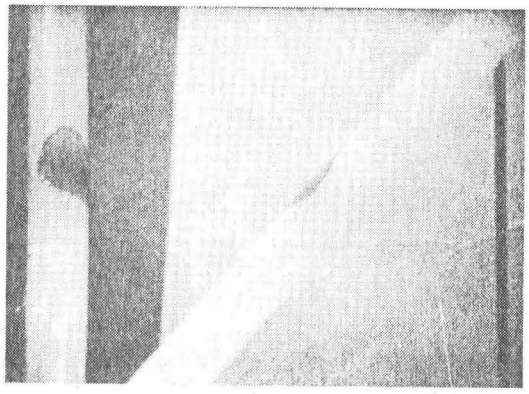


7.02 msec

Fire-Trol 931



2.46 msec



4.92 msec

Figure 23. Selected Frames from the Impact of a Falling Drop of Phos-Chek XA and Fire-Trol 931 With a ½ Inch Polyethylene Dowel at 45°, V_i=12 ft/sec.

Figure 24 shows the splatter patterns for a sequence of impacts ranging from grazing (large off-center) impact to central (axial) impact for Fire-Trol 931. Above each pattern is given the percentage of liquid retained on the dowel (the remainder is on the splatter card). At just grazing impact (the first picture) little breakup of the drop occurred on the dowel, which resulted in a nearly compact splotch being produced on the impactor card on one side of the dowel. The fraction of the liquid retained on the dowel was very small. The splotch produced on the impactor card is close to the dowel and is nearly representative of a free-falling drop except for a small degree of lateral flow and jetting (shown by the spikes and rays) imposed on the outward side of the pattern by the impact.

As the impact position of the drop on the dowel moves toward the axis, i.e., becomes more central, the splotch position on the card moves outward away from the dowel, and the percentage of liquid retained on the dowel increases. The size of the splotch generally decreases, and the pattern exhibits increased effects of outward fluid jetting, breakup and spray formation. Numerous fragments of liquid of various sizes (including many small particle spots lost in the photographic reproduction process) are produced. The degree of liquid breakup increases as the impact point becomes more central. As the impact point approaches the axial (central) position, some liquid splatter also appears on the opposite side of the dowel. For a completely central impact, the liquid becomes completely broken up into droplets by the impact and the splatter pattern of the droplets is essentially symmetrical on both sides of the dowel.

3.3.6.2 Effect of Fluid Composition

The general characteristics of the splatter patterns shown in Figure 24 for Fire-Trol 931 were also obtained for Fire-Trol 100 and water. However, the patterns obtained from Phos-Chek XA differed in that they were always compact and little breakup of the liquid into small droplets occurred, even for central impact (Figure 25). This is quite likely the result of the elastic behavior of the liquid. Figure 26 compares the splatter patterns of a medium sized droplet of the retardants impacting centrally with a 1/4 inch birch dowel. The difference in splatter pattern between Phos-Chek XA and the other three solutions is well illustrated here.

3.3.6.3 Effect of Dowel Size and Composition

Figure 27 shows a comparison of the splatter patterns produced by medium sized drops of water, Fire-Trol 931 and Phos-Chek XA impacting centrally with a dry 1/4 and 1/2 inch birch dowel (the drop height was 42 ft). The patterns of each retardant are essentially the same for both size dowels, except that the pattern is displaced further away from the axis for the larger diameter dowel. Thus dowel size has little effect on the liquid spray produced by impact, but affects its location.

Figure 27 also shows a comparison of the splatter patterns produced by drops of the preceding retardants impacting with 1/2 inch birch and polyethylene dowels. For Phos-Chek XA there is no significant difference between the patterns produced by the two different composition dowels. For each dowel the splatter pattern consists largely of a single coherent blotch

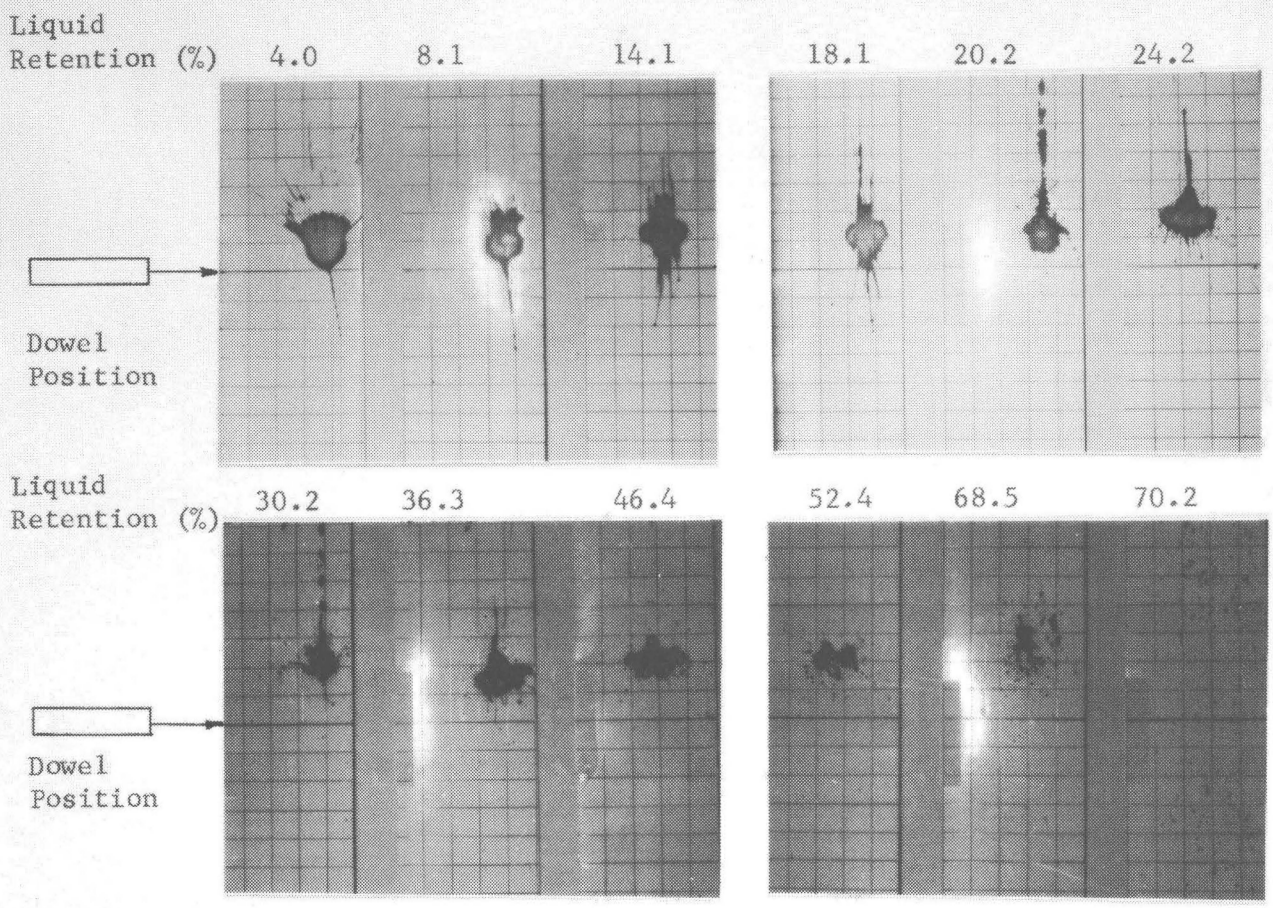


Figure 24. Splatter Patterns of Off-Center versus Central Impacts of a Falling Drop of Fire-Trol 931 (4.4 mm diam.) on a 1/2 Inch Polyethylene Dowel (Drop Height = 42 ft).

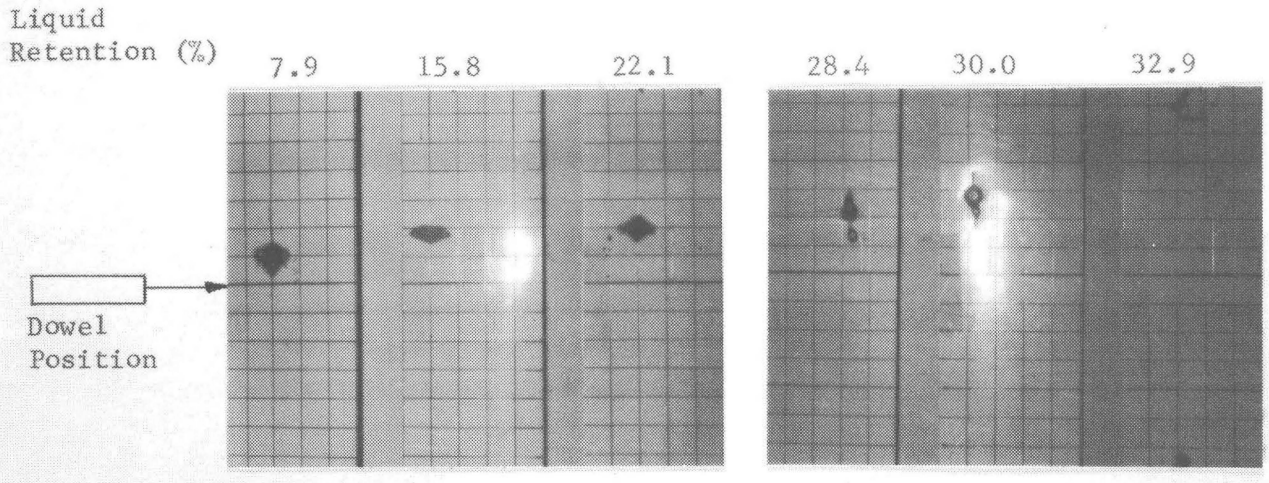


Figure 25. Splatter Patterns of Off-Center versus Central Impacts of a Falling Drop of Phos-Chek XA (4.8 mm diam.) on a 1/2 Inch Birch Dowel (Drop Height $\simeq$ 42 ft).

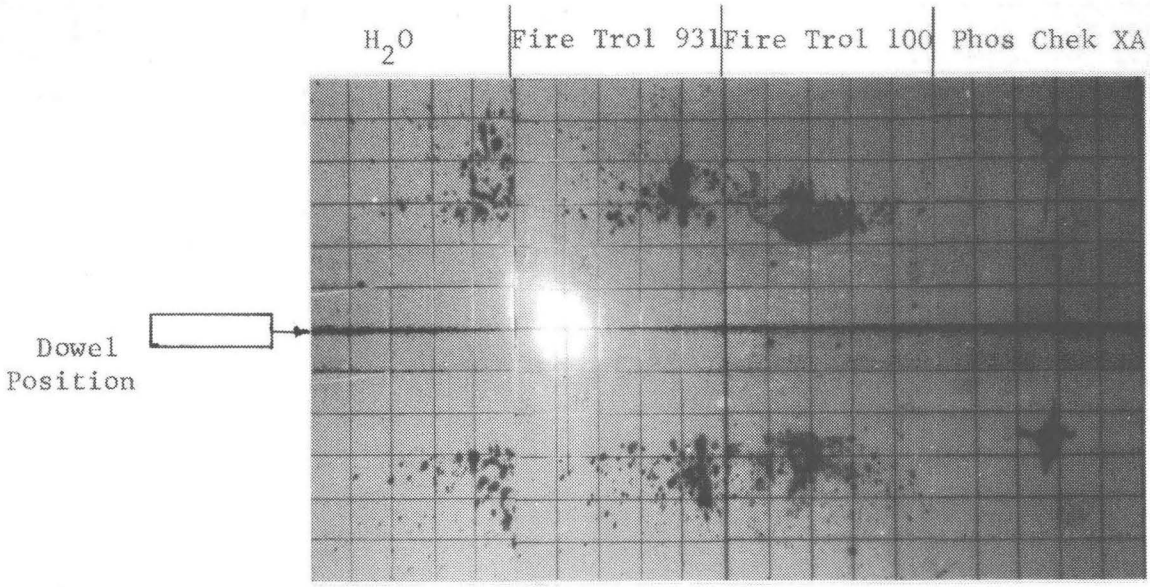


Figure 26. Splatter Patterns of Falling Drops of the Retardants (4.2-4.9 mm diam.) Impacting Centrally With a 1/4 Inch Birch Dowel, Drop Height = 42 ft.

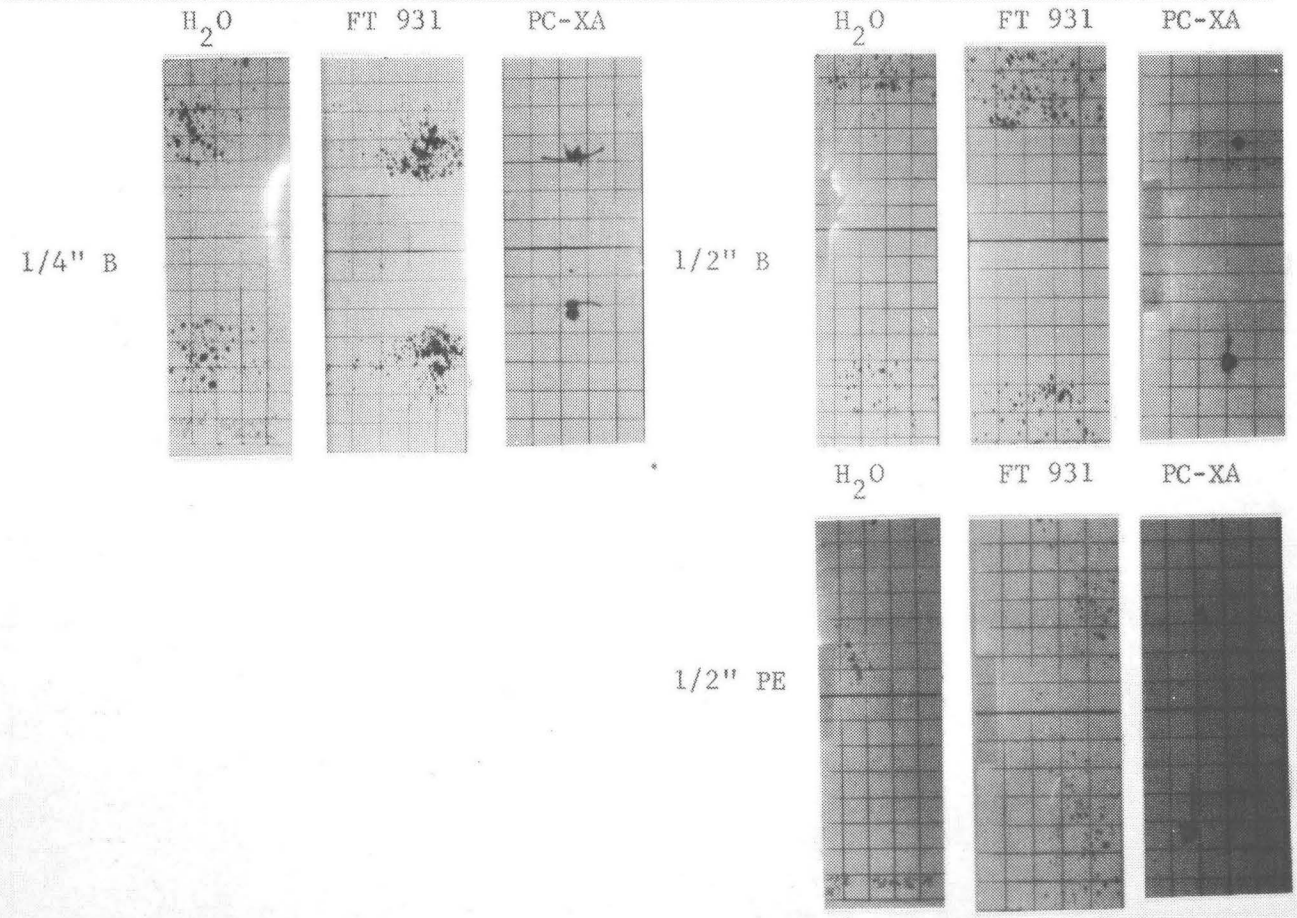


Figure 27. Splatter Patterns of Falling Drops of Retardants (4.2-4.8 mm diam.) Impacting With 1/4 and 1/2 Inch Birch and 1/2 Inch Polyethylene Dowels. Drop Height = 42 ft.

located symmetrically on each side of the dowel. In some cases there was also one or two small additional satellite blotches but never fine spray splatter. The immediate region around the dowel was always free of splatter.

On the other hand the splatter patterns of water and Fire-Trol 931 (also Fire-Trol 100) consisted of spray (droplet) splatter rather than coherant masses, as discussed previously. In the case of the birch dowels this splatter was located, symmetrically, at some distance from both sides of the dowel axis. However, for the polyethylene dowel the spray splatter from water and Fire-Trol 931 drops also extended inward underneath the dowel (to its axis) on both sides of the dowel (Fire-Trol 100 was not dropped on the polyethylene dowel at 42 ft). This indicates that the liquid flow over the dowel during impact penetrates over a larger circumferential area for the polyethylene dowel than for the birch dowel. This behavior may be due to the smoothness (low surface friction) of the polyethylene dowel, and appears to occur only with the low viscosity (including shear-thinning) liquids.

Since the splatter pattern for Fire-Trol 100 with the polyethylene dowel was not obtained, it is not known whether it is similar to that of water and Fire-Trol 931.* In this case however, the high speed photographs given in Figures 16 and 17 showed that the Fire-Trol 100 had a tendency to wrap-around the polyethylene dowel, and Figures 20 and 21 showed that Fire-Trol 931 also wrapped around the dowel. Since the liquid retention on the dowel of the two Fire-Trol fluids was about the same, this indicates that the wrap around results in the ejection of spray droplets immediately below the dowel, as well as from its sides.

3.3.7 Drop Evaporation During Free Fall

The experimental data obtained in the preceding studies using the 40 ft tower assumed that no mass loss of the liquid occurred by evaporation during the free fall of the drops. In order to evaluate the general validity of this assumption, a study was conducted in which the average weight of drops falling from a few inches and the average weight of drops after falling from the 42 ft drop height were compared. Medium sized (4-5 mm) drops were used in the studies and were prepared in the manner discussed earlier. In conducting the experiments a 500 ml beaker was placed on the Arbor balance, and using the tare function the average weight of a series of drops that were dropped from several inches and from the drop tower determined. The difference between these weights was assumed to be due to evaporation. In the case of water, Fire-Trol 931 and Phos-Chek XA the tests were conducted using 10 drops in a series. With Fire-Trol 100 however, the weighings were performed on single drops since it was difficult to hit the beaker in the drop tower drops.

Table VII summarizes the results of the studies. Water and Fire-Trol 100 undergo the most evaporation, and the weight loss by evaporation of Fire-Trol 931 is somewhat surprisingly significantly less than for the other fluids. The magnitude of the weight loss is sufficiently small in all cases that it does not affect the general results or conclusions of the preceding work. For example the percentages of weight loss by evaporation given in Table VII will affect the percentages of liquid retention shown in Figure 5 by only a few percent in the worst cases.

* However the splatter produced using the polyethylene dowel trees (Section 4.3) indicates the splatter patterns are the same for these three fluids.

TABLE VII. DROP EVAPORATION DURING FALL FROM THE DROP TOWER*

Liquid	T °F	M_i mgm	σ mgm	d mm	M_f mgm	σ mgm	d mm	% Weight Loss
Phos-Chek XA	68	654.1	18.3(10)	4.88	620.7	12.5(18)	4.80	5.1
Phos-Chek XA	90	610.1	32.3(25)	4.77	559.8	13.7(20)	4.64	8.3
Fire-Trol 100	82	64.1	5.3(60)	4.77	55.9	2.8(64)	4.56	12.8
Fire-Trol 100	82	59.0	4.8(60)	4.64	54.1	2.9(50)	4.51	8.2
Fire-Trol 931	77	479.5	12.1(10)	4.38	465.9	13.9(15)	4.34	2.8
Fire-Trol 931	97	467.0	23.2(10)	4.34	457.1	17.2(40)	4.31	2.1
Water	86	464.9	16.3(11)	4.46	416.5	18.1(34)	4.30	10.4
Water	104	419.2	11.6(10)	4.31	318.1	20.1(20)	4.18	9.1

* The weights (M), standard deviations (σ) and drop diameters (d) are averages. The number in parenthesis indicates the number of tests using a series of drops. i = Initial, f = Final.

4. RETARDANT WETTING OF SIMULATED FUEL STRUCTURES

Subsequent to the dowel impact studies with single drops just discussed, studies were conducted on 3 dimensional dowel trees that simulate real fuel structures in order to determine the individual and cumulative effects that successive individual liquid drops have on the overall wetting process. The basic target structure used for these tests was a simulated tree made up of dowels, which for simplicity will be referred to merely as a dowel tree . Both birch and polyethylene dowels were used in the construction of the trees.

4.1 FUEL STRUCTURE DESIGN AND EXPERIMENTAL PROCEDURE

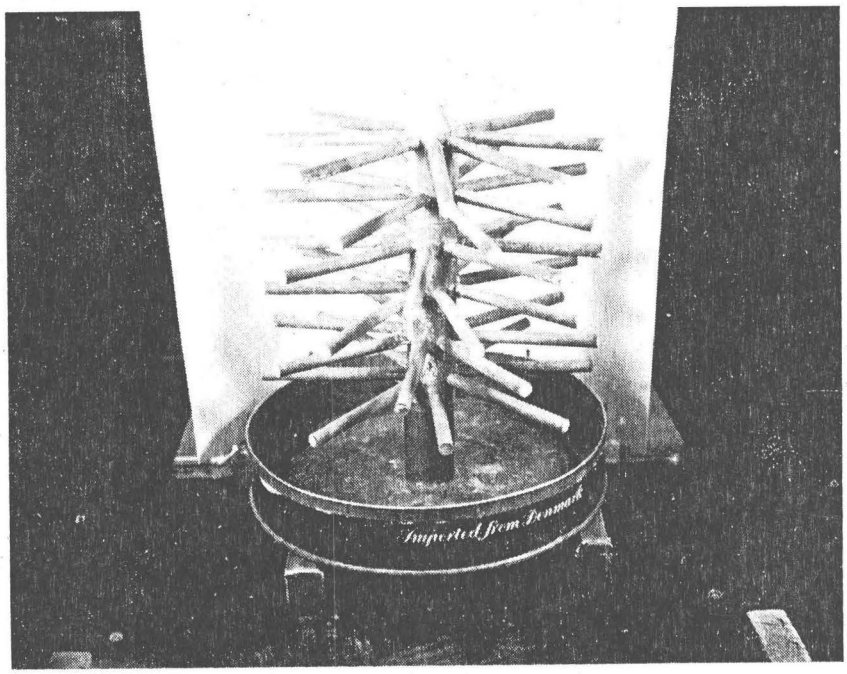
The general design of the basic dowel tree is shown in Figure 28. The tree consisted of three detachable sections. A 1 in. diam., 6.375 in. long dowel cut into 3 sections was used as the stock (trunk), and 48 dowels (3 in. long, 0.25 in. diam.) were used as the primary branches. Each section of the stock was made up of a central hub with two layers (1 in. apart) of limb spokes, 8 spokes (45° apart) on each layer. The spokes in the lower layer of a hub were offset from those in the upper layer so as to bisect the angle formed by the spokes in the upper layer. The central hub of the middle and bottom sections were both 2 in. long, while the length of the top section was 2.375 in. including a 1/2 in. long taper. The limb dowels were glued in 1/4 in. deep holes drilled into the hubs. The effective diameter of the tree dowels was thus about 6.5 in. (there were small variations in hole depth and dowel length). In the construction of a tree, the three sections were rotated with respect to each other in a manner as to minimize the free space that would be available to a liquid drop falling vertically through the limbs, i.e., to maximize the probability of a vertically-falling drop hitting a limb.

A 1/4 in. diam. 8.25 in. long aluminum rod attached to a 5 in. x 5 in. x 1/4 in. Teflon base served as a supporting pole for the detachable tree sections. A 5/16 in. hole was drilled axially through the bottom and middle hubs and half way through the top hub for mounting the hubs on the pole, as shown in Figure 28. A washer was fixed on the rod 1.25 in. from the base, and 2.375 in. higher a pin was inserted through the rod. A liquid collecting pan (7.5 in. diam., 1.5 in. deep) with a central hole mount (to prevent leakage) was located between the washer and the pin. The bottom section of the dowel tree rested on the pin, with the middle and top sections above it.

4.1.1 Experimental Procedure

The experiments consisted of dropping individual drops of fire retardant from the top of the 40 ft drop tower through the metal drop tube onto the dowel tree structure, and measuring the weight of the liquid that was retained on each section of the tree and that was deposited in the pan. Additional information was obtained by visual observation, photography and splatter cards. In this manner information was obtained regarding the splatter, drip and run characteristics produced by each drop (or a series of drops), and the cumulative effects of the drops.

In conducting the experiments the Arbor balance was placed



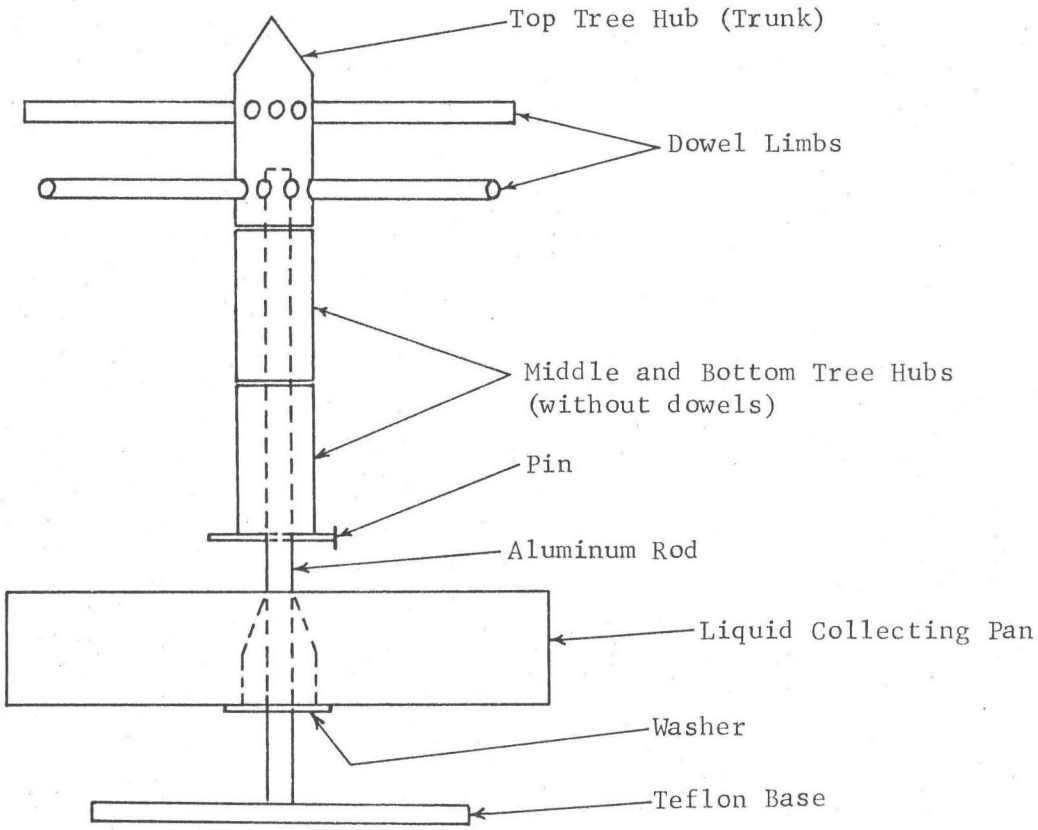


Figure 28. Basic Dowel Tree Structure with Liquid Collecting Pan.

beneath the metal shield (Figures 1b, 2b) in the small plywood enclosure beneath the metal drop tube of the drop tower (section 3.2.1). The Teflon base of the dowel tree rested on the weighing pan of the scale, and the aluminum rod passed up through a 1/2 in. hole in the top of the shield. The liquid collecting pan and dowel tree were supported by the rod above the shield. During the dropping of a series of individual drops on the tree, the pan was raised slightly above its washer base and supported on a plywood platform. The scale then weighed only the dowel tree, the Al rod and Teflon base. Using the tare function, the scale gave the total retained weight of the retardant on the tree at all times. By manually removing the top and middle sections individually, the retention on each tree section could be calculated (the weight of the individual dry sections were known). By lowering the collecting pan onto its washer base on the stand, the weight of the liquid which was collected in the pan by run, drip and direct impaction could also be obtained.

4.2 WETTING CHARACTERISTICS OF THE BIRCH DOWEL TREE

The birch dowel tree was made of smooth birch, and constructed in the manner just described. The birch was the same as used in the single dowel experiments of section 3. The experiments consisted of dropping a fixed quantity of liquid retardant a drop at a time from the top of the drop tower onto the dowel tree located beneath the metal drop tube, and then weighing the liquid retained on the tree and in the pan and observing the appearance of the liquid on the tree. The procedure was then repeated. In practice the quantity of liquid dropped between weighings was 10 cc for water and Fire-Trol 931 (corresponding to about 200-240 drops), and 200 individual drops of Fire-Trol 100 and Phos-Chek XA. The retardants were prepared as in section 3.2.4. In dropping the drops, the position of the eye dropper at the top of the drop tube was continuously varied over about a 6 inch diameter circular area to help insure that the position of the consecutive drop impacts on the tree was essentially random. In addition, as discussed previously, the drops often underwent some (usually random) lateral motion during fall due to thermal or convective currents in the drop tube.

4.2.1 Liquid Recovery and Splatter

Not all of liquid dropped from the top of the drop tower was recovered on the dowel tree and the collecting pan beneath the tree. A portion of the liquid was lost to the sides of the drop tube during the falling of the drop, a portion was lost as side splatter or spray as the drops impacted the tree, and a portion was lost by drops that hit outside of the tree and pan*. This latter loss was generally quite small. The top left hand figure in Figure 29 shows the experimental percentage recovery of the liquid in the pan and tree as a function of the quantity of liquid dropped. This quantity is expressed as gallons per 100 ft^2 of impact area (gpc) in order to best relate it to field practice, the impact area being based on the area of the pan. Since the cross sectional area of the tree was a little smaller than the area of the pan, the effective gpc on the tree would be smaller. Based on relative areas, the gpc on the tree would be a factor of $(6.5/7.5)^2 = 0.751$ smaller than the gpc on the pan. However, the actual factor is probably higher since most of the falling drops appeared to interact with the tree.

* A portion of the liquid was also lost by evaporation, see p. 64.

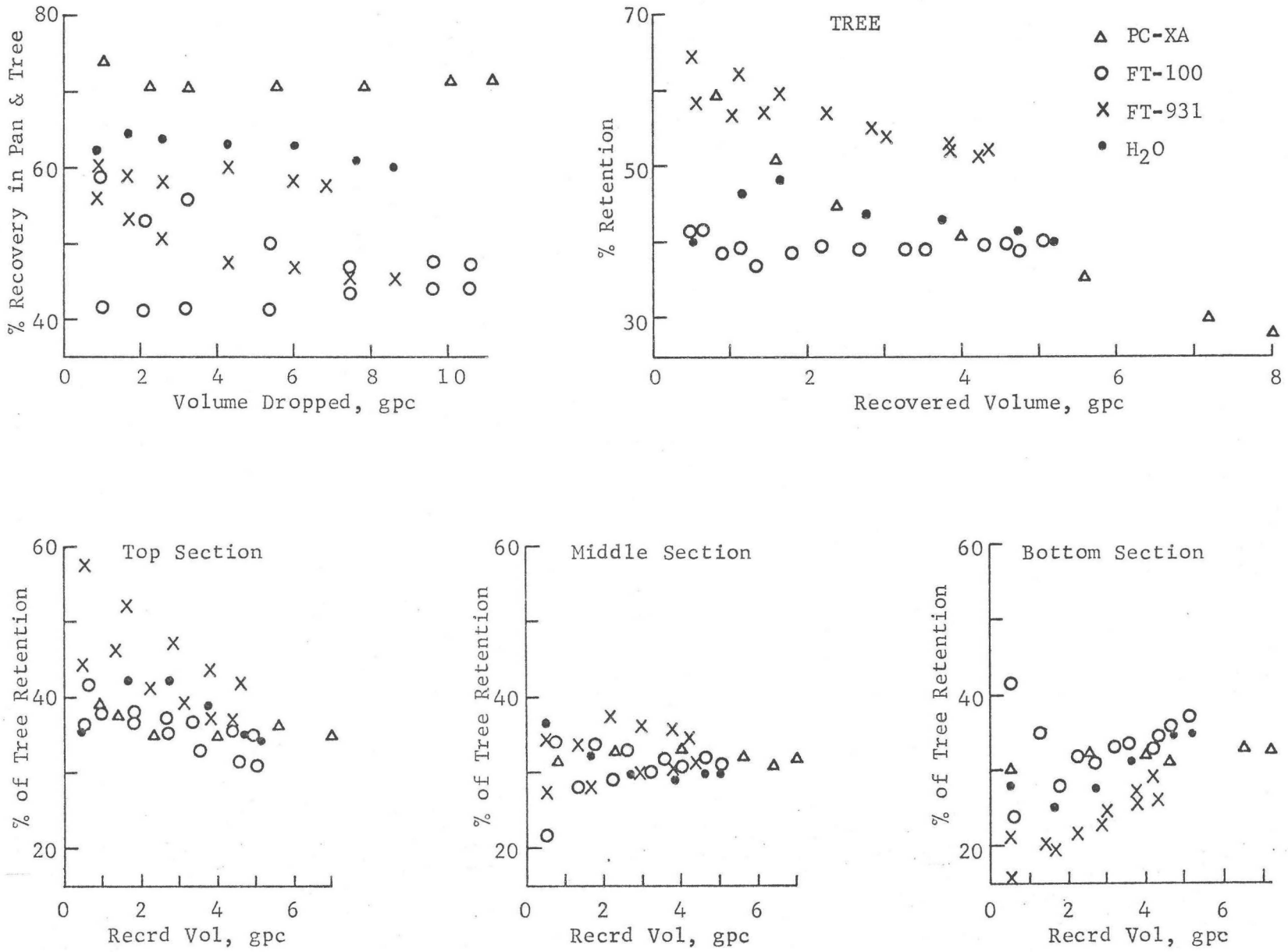


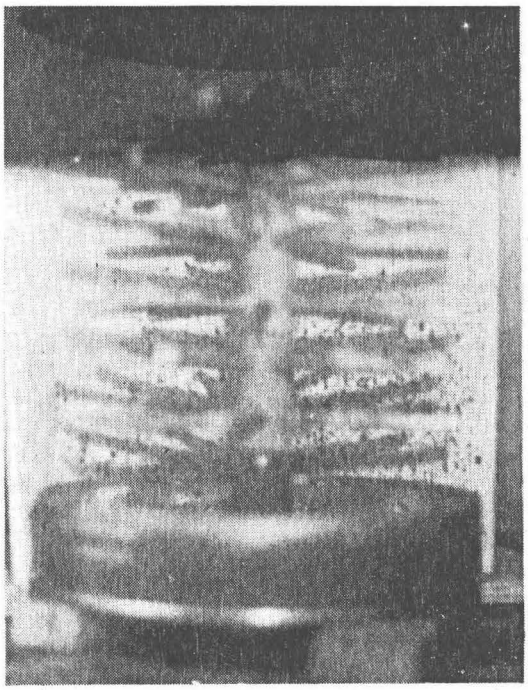
Figure 29. Experimental Retention of the Impacted Liquids (4-5 mm Drops) on the Birch Dowel Tree and Its Individual Sections.

The preceding figure shows that the greatest recovery of the dropped liquid (in the pan or on the tree) was obtained with Phos-Chek XA; with water, Fire-Trol 931 and Fire-Trol 100 following in the given order. Two experiments were conducted on each of the two Fire-Trol fluids and a comparison of the two sets of data for each fluid gives information regarding the reproducibility of the tests. The recovery of the various fluids was generally relatively insensitive to the volume dropped within the accuracy of the measurements. Since the weighings were made after dropping every 200 drops or so, a large number of data points was obtained. It was not useful to plot all these points, and in general only about half (often every other one) of the data points were used in this and all the other plots to be discussed. Occasionally when needed data points (e.g., at the end of a curve) of two different fluids were the same, one was displaced slightly in the plot to allow the points to be distinguished. Some difficulty was experienced in determing the best manner in which to present the various data. It was decided that several relatively small plots on one page that enables a rapid and simultaneous comparison of the various fluids and tree segments would be most useful as it visually enables trends to be picked out which are lost by larger plots contained on several pages.

The liquid recoveries in Figure 29 range from about 70% for Phos-Chek XA to a little over 40% for Fire-Trol 100. The relative ordering for these two fluids is consistent with experience in dropping the liquids through the drop tube, which has always shown that Phos-Chek XA drops are most efficient in getting down through the tube, and Fire-Trol 100 is least efficient. However a significant portion of the lost liquid was also due to side splatter during the impact of the drops with the tree. In the experiments a witness card (same paper as in section 3.2.2) was supported in a vertical position around the back half of the tree (Fig 30). The card was 10 inches high and formed a roughly 8 inch diam. semicircle. The card collected the side spray and splatter produced during the impact of the drops with the tree. Figure 30 illustrates the splatter produced by 10 cc of the various fluids. The splatter patterns of water, Fire-Trol 100 and Fire-Trol 931 were always similar in the sense that the entire card was contaminated with spray and fragments of broken up liquid, including an occasional jet. The size of the stains ranged from very small specks and dots to roughly 1/4 inch or more diameter splotches. On the other hand the witness cards from Phos-Chek XA were essentially free of any small spray or splatter, but usually contained a few relatively large sized splotches as well as an occasional jet. The amount of liquid lost by side splatter was generally significantly larger for water and the two Fire-Trol fluids than for Phos-Chek XA. Since it was necessary to replace the cards after every 10 cc of dropped liquid and they were roughly similar after each 10 cc dropped, only several representative cards were collected on each test.

4.2.2 General Observations

The general behavior of the drops of the various impacted fluids on the tree differed to some degree, and in some cases the difference was quite significant. During the dropping of the liquids, the drops would impact randomly with various branches on the tree. For water and the two Fire-Trol fluids the initial impacts would produce splatter and simultaneously wet a portion of the tree where the impact occured. Secondary impact on a



Splatter Card in Position
Behind Dowel Tree.
(Focused on the Card)

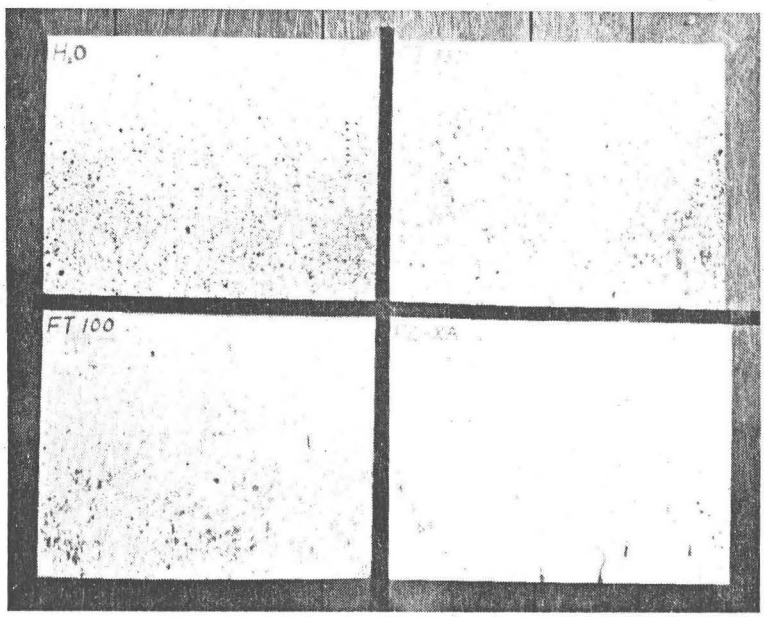


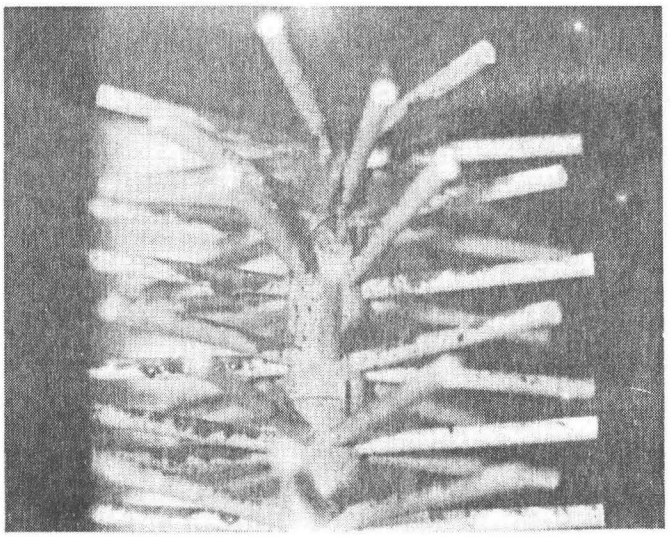
Figure 30. Side Spatter Produced by About 200 Consecutive Drops of Liquid Impacting with the Birch Dowel Tree (Back Half of Tree).

wetted area would increase the rate of spreading (running) of the liquid over the tree surface. In the case of Phos-Chek XA the initial impacts resulted in a wetting in the same general manner, except that little lateral splatter and no spray was produced by the impact.

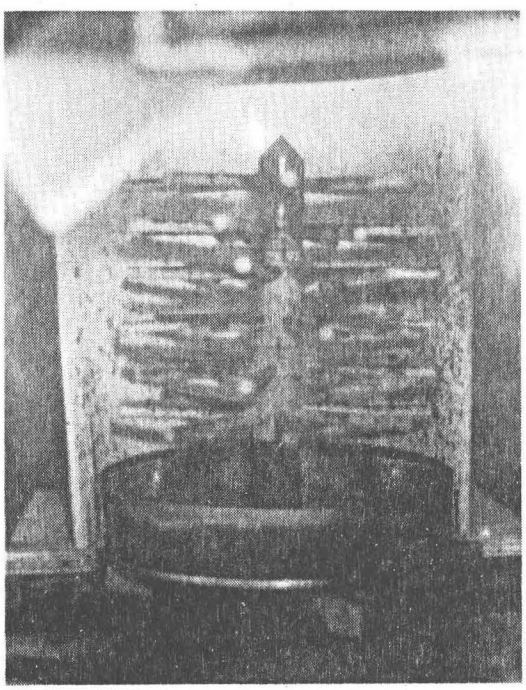
After about 1 gpc of water or Fire-Trol 931 had been dropped on the tree, hanging drops from the coating of liquid around the branches began to form which gradually grew larger. These drops began breaking and dropping onto lower branch levels (or the pan) after about 3 gpc of Fire-Trol 931 or 5 gpc of water had been dropped. In the case of Phos-Chek XA the hanging drops began forming after only about 0.4 gpc of added liquid, and some began breaking almost simultaneously. The rate of drip increased rapidly with increase of added liquid. For Fire-Trol 100 there was no dripping throughout the entire experiment. This general behavior of fluid drip appears to correlate to the relative surface tensions of the liquids (Table III), i.e., low liquid surface tension enhanced drip and high surface tension impeded it. Figure 31 and 32 illustrate the appearance of the tree dowels during the dropping of the various retardants. The most significant observation is the relatively extensive dripping of Phos-Chek XA, and the non-dripping of Fire-Trol 100. Dripping of Fire-Trol 931 and water also occured, with the ease of dripping of Fire-Trol 931 being greater than that of water. The lack of clarity in some of the pictures is due to the fact that the pictures of the tree were taken through the plexiglas door of the enclosure housing the tree and scale.

The droplet impact behavior also had other affects on the general wetting characteristics of the tree. For water and the two Fire-Trol fluids, the splatter and spray produced during impact caused a partial wetting of the stock as well as of adjacent limbs and the underside of limbs (in addition to fluid wrap around). It also wetted the lower limbs near the stock which were shielded (due to limb density) from direct droplet impact. In the case of water and Fire-Trol 931, as the liquid level increased on localized regions of the stock and branches, the liquid began running and dropping which further wetted the tree in regions not yet touched by droplet impact. Water running down the stock was interrupted and absorbed at the interface between the section hubs of the tree stock, but running Fire-Trol 931 crossed the gaps. The liquids were also absorbed to some degree by the bulk wood of the tree (water was absorbed the fastest). For Fire-Trol 100 there was little flow down the stock, and the stock wetting was due largely to splatter. On the other hand in the case of Phos-Chek XA there was little splatter, and the relatively little stock wetting was due largely to liquid flow from the limbs. The underside of the limbs was wet only by liquid wrap around. The Phos-Chek XA liquid was both partially normal in appearance and partially frothy, as seen in field tests.[6] The breaking of a hanging drop occurred by the necking down of a ligament, as in the case of droplet impact. The retention of the drips on the lower limbs was very efficient until saturation occured.

The liquid flow (run and drip) that occurred during the droplet impacts and tree wetting was non-homogenous, and varied widely in various localized regions of the tree. Generally speaking however, the film thickness of water appeared smaller than for the other liquids, while Fire-Trol 100 was the largest. In the latter case the retardant



After 200 Drops (0.8 gpc) of Dropped Liquid



After 400 Drops (1.6 gpc) of Dropped Liquid

Figure 31. Appearance of the Birch Dowel Tree After Dropping 10 and 20 cc of Fire-Trol 931 on the Tree.

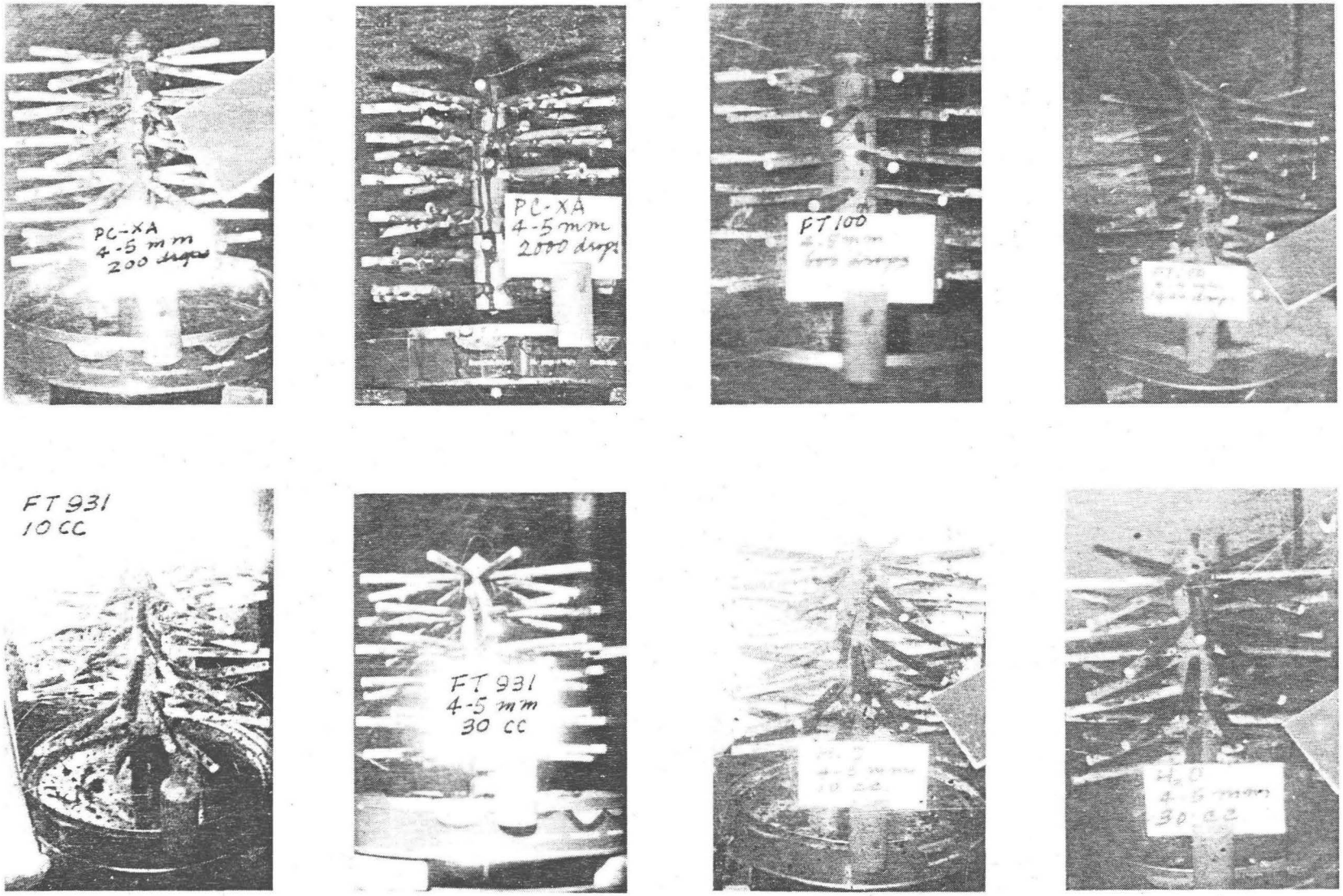


Figure 32. Appearance of the Birch Dowel Trees During the Dropping of the Fluids (10cc ≃ 200 Drops ≃ 0.8 gpc).

coating seemed to be pushed along the dowel limbs as the result of secondary impact. The film thickness of Phos-Chek XA was larger than that of Fire-Trol 931. In summary then, the wetting out of the tree dowel by falling drops of retardant occurred by the conventional mechanism of droplet impact, run and drip. By way of specific differences in retardants, droplet impact of water and the two Fire-Trol solutions on the tree produced side splatter and spray which assisted the wetting out of the stock and limbs; whereas Phos-Chek XA produced little splatter. The droplet impacts of all the fluids produced localized wetting, and subsequent run. In the case of Phos-Chek XA, water and Fire-Trol 931, hanging drops formed by wrap around of the limbs as the liquid built up on localized regions of the tree. The breaking of the drops produced drip onto lower branch elements and the pan. However no drip occurred for Fire-Trol 100. Drip occurred most easily (at the lowest level of dropped liquid) for Phos-Chek XA. Fire-Trol 931 and water followed in that order. The ease of dripping correlates with the fluid surface tension. The buildup of the liquid on the tree dowel during its wetting by impacting drops occurred non-homogeneously. The film thickness of the liquid in the localized wetted regions of the tree was greatest for Fire-Trol 100, followed by Phos-Chek XA, Fire-Trol 931 and water, respectively.

4.2.3 Efficiency of Liquid Retention

The initial studies were conducted using medium size (4-5mm) drops of all four retardants, as this size is prepared most easily. Figure 29 shows the percentage of the recovered liquid (liquid on the tree and in the pan) that was retained on the tree as a function of the recovered liquid in gallons per 100 ft.^{2} of impact area (gpc). The gpc is based on pan area, and the actual gpc on the tree may be a little smaller, as discussed earlier. The fluid retention is given for the entire tree, as well as for its three individual sections.* It may be seen that Fire-Trol 931 was retained most efficiently in the top section of the tree, followed by water, and that the percentage of retention decreased (roughly linearly) with increase in recovered volume. Consequently the retention in the bottom section of the tree was lowest for Fire-Trol 931, followed by water, and the retention increased with increase in volume. The retention of Phos-Chek XA and Fire-Trol 100 was about the same in the top section, and decreased more slowly with recovered volume than the other two fluid (Phos-Chek XA was almost constant). The relative retention of all the fluids was greatest in the top section of the tree, followed by the middle and bottom sections in that order, as might be expected. However the retention on the individual sections tend to become nearly equalized at large fluid volumes, as would be expected after the tree becomes saturated.

The liquid that was most efficiently retained in the tree as a whole up to large fluid volumes was Fire-Trol 931, followed by Phos-Chek XA, water and Fire-Trol 100 in that order. However the percentage retention of Phos-Chek XA decreased strongly with increase in volume (due to dripping); whereas the decrease was more gradual for Fire-Trol 931 and water, and the retention was constant and independent of volume for Fire-Trol 100.

---

* The % Retention for the tree is the % of the recovered fluid volume (gpc); whereas the retention in the tree sections is given as % of the liquid retained on the total tree. The retained volume (gpc) in any tree section at any specified gpc of recovered volume is: gpc (section) = (gpc x fractional retention on tree x section fraction of tree retention).

It should be noted in Figure 29 and the forthcoming related figures that a finite time was required to conduct each experiment, which consisted of a repeated sequence of dropping the liquid and weighing the tree. During this time a partial evaporation of the impacted liquid most likely occurred, and the evaporation effect would not necessarily be the same for the various liquids or a repeat of the same liquid (see Table VII). Thus there is probably an evaporation effect in the measurements whose relative magnitude cannot be evaluated, although it is believed to be generally secondary to the retention effects due to other factors (especially near the beginning of an experiment). The time to conduct an experiment on the three section tree was usually about 1.5 to 2 hrs. However the experiments were conducted during different days (and different times of the day) over a period of time, so that the ambient temperature and humidity usually differed to some extent in the various cases. The experiments were conducted in the closed chamber housing the dowel tree and scale, and this helped to control the ambient conditions around the tree. A small (6" x 6") trapdoor was inserted in the main plexiglas door, and was opened to conduct the weighings (rather than the door) in order to preserve the chamber environment as much as possible.

4.2.4 Average Film Thickness

As noted before, the impacted liquid retardant was retained in the dowel tree in a non-homogeneous manner, and the film thickness of this liquid also varied in the tree. For comparison purposes however, it was convenient to compute the fluid retention in terms of the average film thickness that would be obtained if the retained fluid was distributed evenly over the entire area of the tree (or its sections). The average film thickness, T, at a specified recovered fluid volume (gpc) is given by

$$T = m/\rho_o A \ * \qquad (3)$$

where m is the weight of the retained liquid, A is the surface area of the tree (or its sections) retaining the liquid weight m, and ρ_o is liquid density. The surface area used for the three section tree was 263.47 cm^2, and each of its three sections was assumed to have an area one-third this value, i.e., 87.82 cm^2. The fluid densities are given in Table III.

Figure 33 shows the average film thicknesses of the fluids in the birch tree and its individual sections, based on the experimental weight of retention measurements and Eq.(3). The average film thickness increases roughly linearly with increase in recovered fluid volume, and generally reflects the behavior of the retention curves in Figure 29. Thus the film thickness of the top two sections was greatest for Fire-Trol 931, and of the bottom section was greatest for Phos-Chek XA (due to drip). At large recovered volumes the film thickness of Phos-Chek XA begins to droop (becomes nonlinear), which causes it to then become smaller than those of the other fluids. The film thickness at a particular fluid volume was greatest for the top section, followed by the middle and bottom section, respectively.

For the tree as a whole, the film thicknesses of Fire-Trol 931 and Phos-Chek XA were the greatest at small fluid volumes, but Phos-Chek XA increased the more slowly with increase in volume. Thus over the fluid volume range of most interest, Fire-Trol 931 had the largest film thickness,

---

* For a tree, this equation is equivalent to: $T_t = (0.1161/A)$(% Retention x gpc); for a tree section, T = (% of Tree Retention/100) T_t.

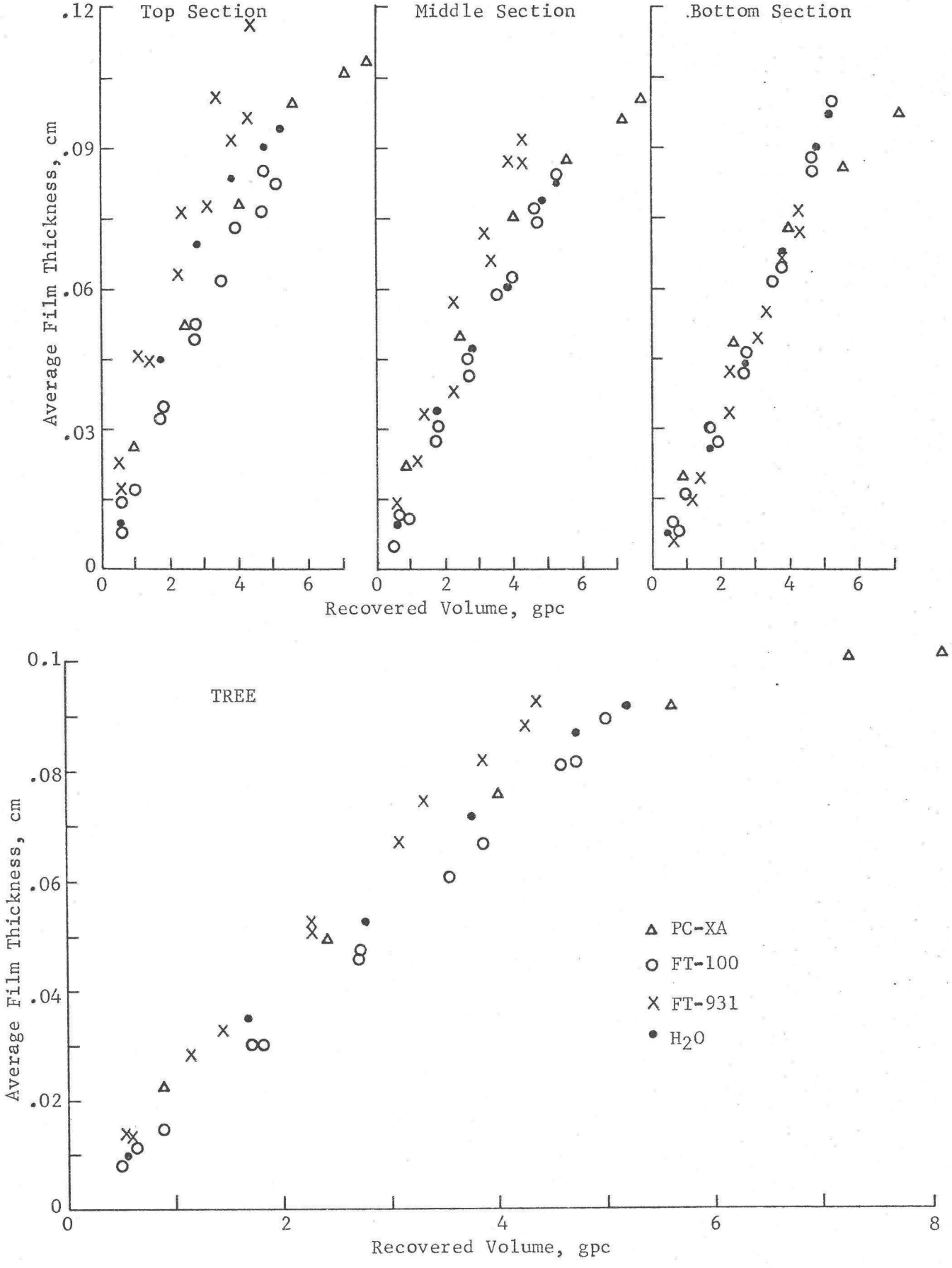


Figure 33. Average Film Thickness of the Retained Liquid (4-5 mm Drops) on the Birch Dowel Tree and Its Individual Sections.

followed by Phos-Chek XA and water (which were about the same), and then Fire-Trol 100.

4.2.5 Effect of Drop Size

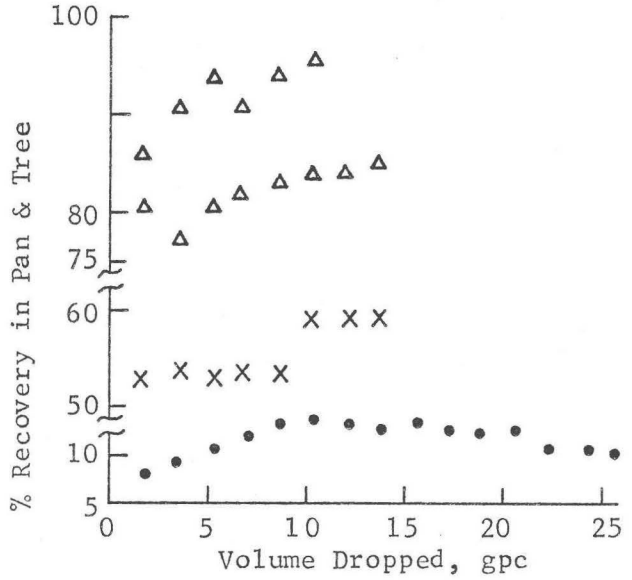
Some experiments were also conducted to study the effect of drop size on the wetting of the birch dowel tree, since the drop sizes of the retardants differ in the field, as discussed previously. Two tests were conducted with Phos-Chek XA having an average drop diameter of about 7mm, two tests with water having a drop diameter of about 2mm, and one test with Fire-Trol 931 having a drop diameter of about 2mm. The recovery of the liquid on the tree and pan as a function of the volume dropped is shown in Figure 34. A comparison with Figure 29 indicates that increasing the drop size of Phos-Chek XA increased its recovery on the tree and pan a modest amount. Decreasing the drop size had little effect on the recovery of Fire-Trol 931, but reduced the water recovery very significantly. The reduction appeared to be due to larger loss in the drop tube. The impact splatter and spray characteristics of the retardants appeared to be about the same as for the medium sized (4-5mm) drops, although the quantity of splatter for water appeared to decrease. Also, no obvious differences in the impact, run and drip characteristics were observed from those of the medium sized drops.

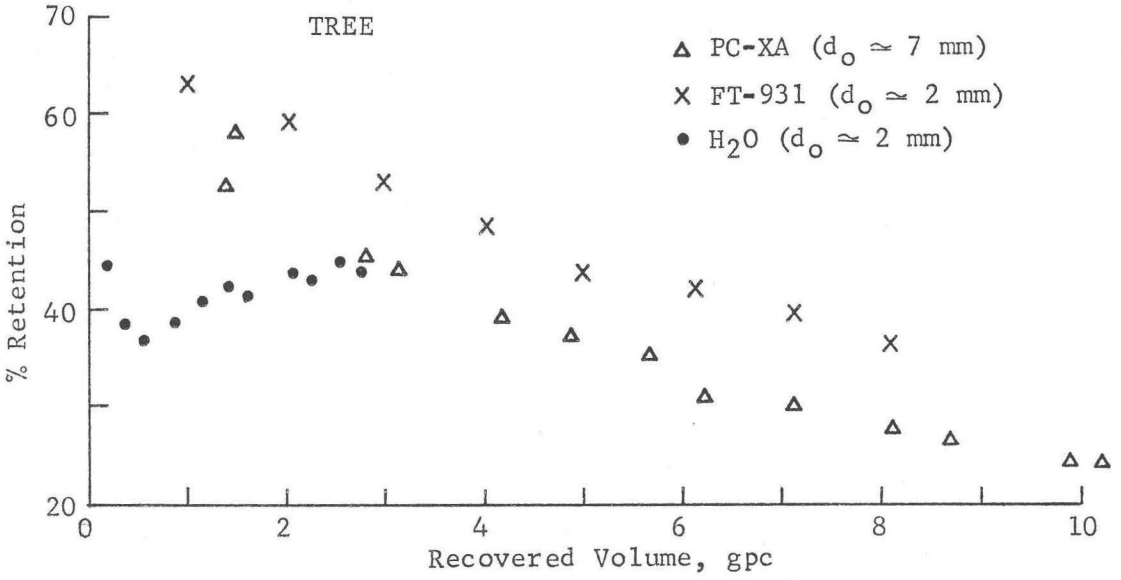
The retention efficiency of the recovered liquids on the tree dowel is also shown in Figure 34. There are generally only small differences between the fluids in the individual sections of the tree. As for the medium sized drops, the fraction of retained liquid was greatest in the top section of the tree, followed by the middle and bottom sections, respectively. In the tree as a whole, however, Fire-Trol 931 had the largest retention at all fluid volumes. The retention efficiency of water was relatively constant with increased volume, but that of Fire-Trol 931 and Phos-Chek XA both decreased (due to drip).

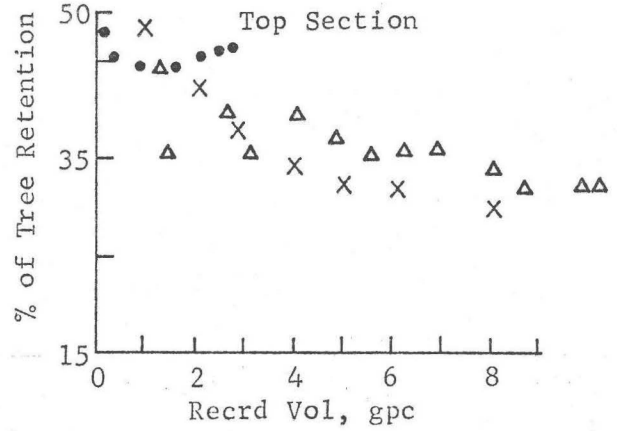
The average film thickness of the retardants is shown in Figure 35. As in the case of retention efficiency, the differences between the retardants on the individual sections of the tree are generally small and on a statistical basis may not be real. Likewise on the tree as a whole the difference between the retardants is small, but Fire-Trol 931 appears to hold a slight edge on film thickness. Based on the preceding results it would appear that drop size has little effect on the wetting characteristics of a fuel such as the rigid birch dowel tree used in the studies. These conclusions would not necessarily hold for all other type of fuel structures however, such as tall grass and lightly supported leaves.

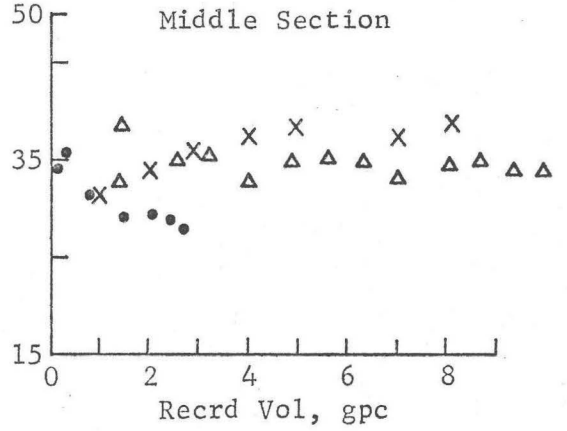
4.2.6 Effect of Extending the Tree Height

In order to obtain further information regarding the effect of liquid run and drip on the wetting out of a multilayer fuel structure (and the consequent distribution of retardant within such a structure), studies were conducted using an elongated birch dowel tree. The tree was made up of two of the basic trees described previously. Its height was thus double that of the trees used in the studies just discussed, and there were 12 limb layers and 96 limbs. The upper limbs thus provided good shielding to the lower limbs, so that most of wetting of the lower limbs could only be attained by drip (and not direct impact). The top half of the tree was made up of 3 sections (discussed previously) that were glued together to form an individual unit of the tree that could be









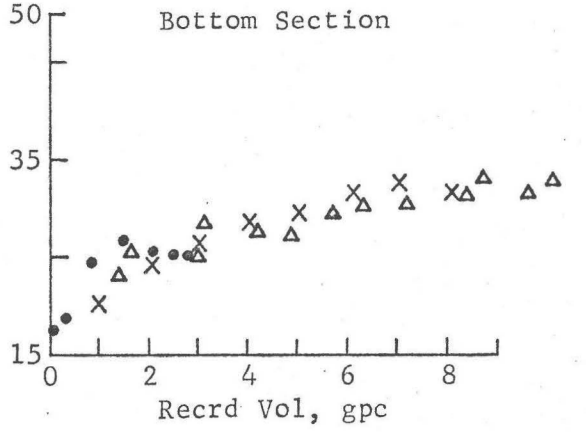


Figure 34. Experimental Retention of the Impacted Liquids (Small & Large Drops) on the Birch Dowel Tree and Its Individual Section.

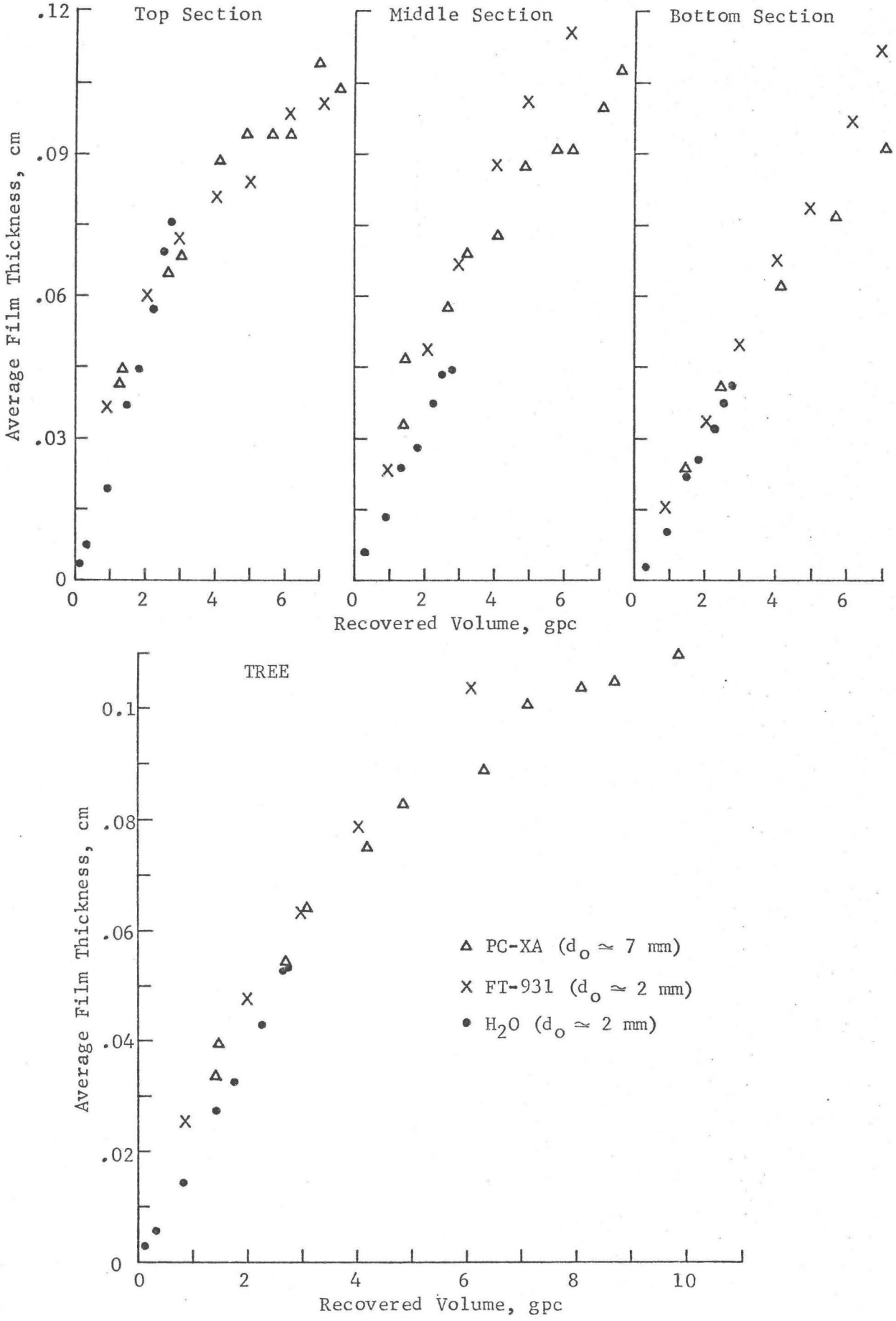


Figure 35. Average Film Thickness of the Retained Liquid (Small & Large Drops) on the Birch Dowel Tree and Its Individual Sections.

removed. In principle the liquid retention on this unit should be essentially the same as for the entire basic tree used in the previous studies. The lower three sections of the tree consisted of 3 detachable individual sections such as used to make up the basic tree. The extended tree thus consisted of four individual units for weighing of the retained liquid, i.e., the top half of the tree (made up of 3 glued sections), and 3 individual lower tree sections.

The experiments were conducted using medium sized (4-5mm) drops of the retardants, one test for each retardant. Figure 36 shows the percentage of recovery of the liquid in the pan and dowel tree. As for the single tree (Figure 29), the recovered liquid was greatest for Phos-Chek XA and least for Fire-Trol 100. The fractional recovery of water and the two Fire-Trol fluids was roughly independent of the fluid volume dropped; whereas the recovery of Phos-Chek XA decreased with increasing volume. The recovery of the first three fluids is less than for the basic tree, and this would occur if the tree extension caused some increased splatter loss for these fluids.

The retention efficiency of the liquids in the tree and its various sections is also shown in Figure 36. The top tree section(top half of the tree) should roughly correspond to the results for the entire tree in Figure 29. Although most of the trends are similar, the absolute retention of the liquids in the top half of the extended tree are significantly greater than for the basic single tree, especially for Fire-Trol 100. This could possibly be due to the fact that the experiments on the basic tree were conducted in April (1977); whereas the experiments on the extended tree were conducted in July when it was much hotter. In both cases the fractional retention of Fire-Trol 931 was greater than that of Phos-Chek XA, and the retention decreased with increase in recovered fluid volume. Also in both cases the fractional retention of Fire-Trol 100 was constant and independent of fluid volume.

The retention of the liquid in the lower three sections (lower half) of the extended tree was much less than in the top half of the tree (Figure 36), as would be expected. The retention of the liquid in the top section of the lower half of the tree was greater than in the middle section below it, which in turn was greater than in the bottom section. Comparing the retention in the top three sections (Figure 29) with that in the bottom three sections (Figure 36) indicates that the retention was greatest in the top section, and decreased monotonically in the five sections beneath it. This shows that the wetting of a multilayer structure occurs in a stratum type fashion, as has been postulated before [15].

The total width of the 16, 1/4 in. diam. limb dowels in a two branch section of the tree is 4 inches. The effective tree diameter, d_e, shielded completely beneath N sections of the tree is given by, $\pi d_e = 4N$. The effective shielded diameter beneath the third, fourth and fifth tree sections is thus 3.8, 5.1 and 6.4 inches, respectively. Since the tree is 6.5 inches in diameter, this calculation shows that the bottom (sixth) tree section is completely shielded from direct droplet impact and can only receive liquid by drip or splatter. The fifth tree section is completely shielded from direct impact over 5.1 inches of its diameter, and the remaining outside area is about 22% shielded by the overhead branch dowels. The fourth tree section is

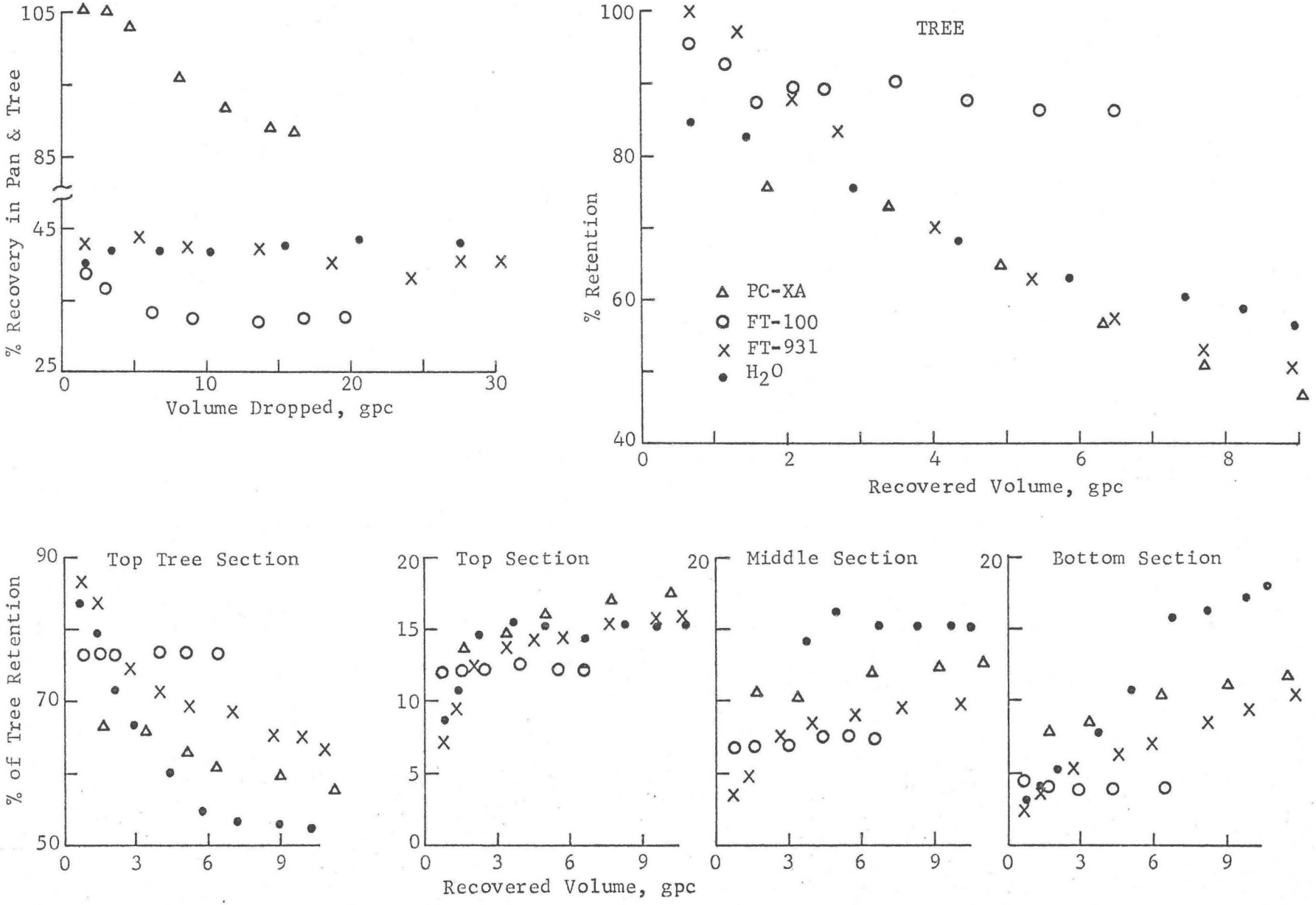


Figure 36. Experimental Retention of the Impacted Liquids (4-5 mm Drops) on the Extended Birch Dowel Tree, and Its Top Half and Lower Three Sections.

completely shielded from direct impact over 3.8 inches of its diameter, and the remaining outside area is shielded about 18% by the overhead branches. This indicates that the bottom two tree sections obtained essentially all of their wetting by drip and splatter (no direct droplet impact). Figure 36 shows that water and Phos-Chek XA are present in the largest quantities in the bottom two sections, followed by Fire-Trol 931 and Fire-Trol 100. This agrees with the hypothesis that the ease of dripping is controlled by surface tension, i.e., lower surface tension gives greater dripping.

The average film thickness of the extended tree and its sections is shown in Figure 37. The film thickness in the top half of the extended tree differs from the basic tree (Figure 33) largely in that Fire-Trol 100 now has the largest thickness (possibly due to higher ambient temperature, as mentioned before). The other trends are similar however. There was little fluid composition effect on the 4th tree section. The bottom two sections have the same behavior as in the retention curves, i.e., water and Phos-Chek XA have the greater average film thicknesses. In the tree as a whole, Fire-Trol 100 had the largest average film thickness, especially at the higher recovered fluid volumes, and therewere only small differences in the other fluids out to large volumes.

4.2.7 Measurment of Liquid Retention by Dowel Immersion

In order to obtain additional information regarding the meaning and limits of the average liquid film thicknesses determined in the studies, measurements were also made of the maximum stable liquid that could be retained by the basic birch dowel tree. The measurements were made by immersing the top and middle sections of the tree in the four retardants and weighing them at various times (the bottom section was identical to the middle section). The difference between the liquid retained on the middle and top section was very small in all cases, except for Fire-Trol 100 which differed by about 10%. The weights of the various sections were averaged to obtain an averaged weight of each liquid on a section.

It was found that very shortly after immersing a tree section in water, Fire-Trol 931 and Fire-Trol 100 there was no obvious dripping, and thus the added mass on the structure was stable except for subsequent evaporation. The initial averaged weights of these liquids on a section was 6.761, 8.121 and 14.519 gm, respectively. The initial stable average film thickness of the fluids on the tree section (the film thickness of the tree is the same) is summarized in Table VIII (the computed average surface area of a tree section is 87.82 cm^2, as described earlier).

After immersion of a tree section in the liquids, the liquid retained on the section underwent evaporation. Figure 38 shows the measured weight of the retained liquid as a function of time (many weight readings not shown were obtained). The evaporation curve of the preceding liquids is linear. After 5 minutes the sections were shaken, and the averaged weight of the retained liquids was 5.903, 7.028 and 9.735 gm, respectively. The corresponding film thicknesses are given in Table VIII.

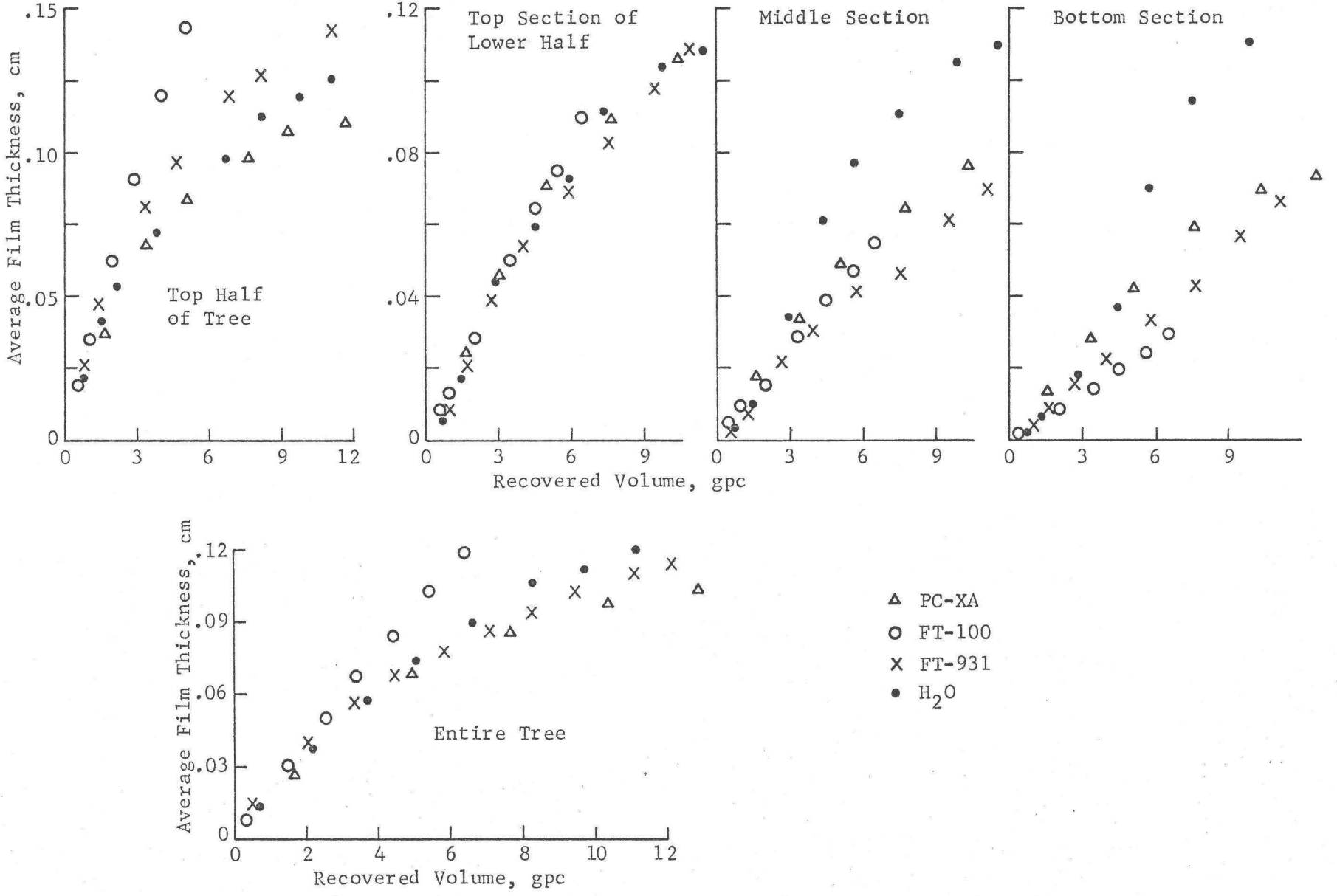


Figure 37. Average Film Thickness of the Retained Liquid (4-5 mm Drops) on the Extended Birch Dowel Tree, and Its Top Half and Lower Three Sections.

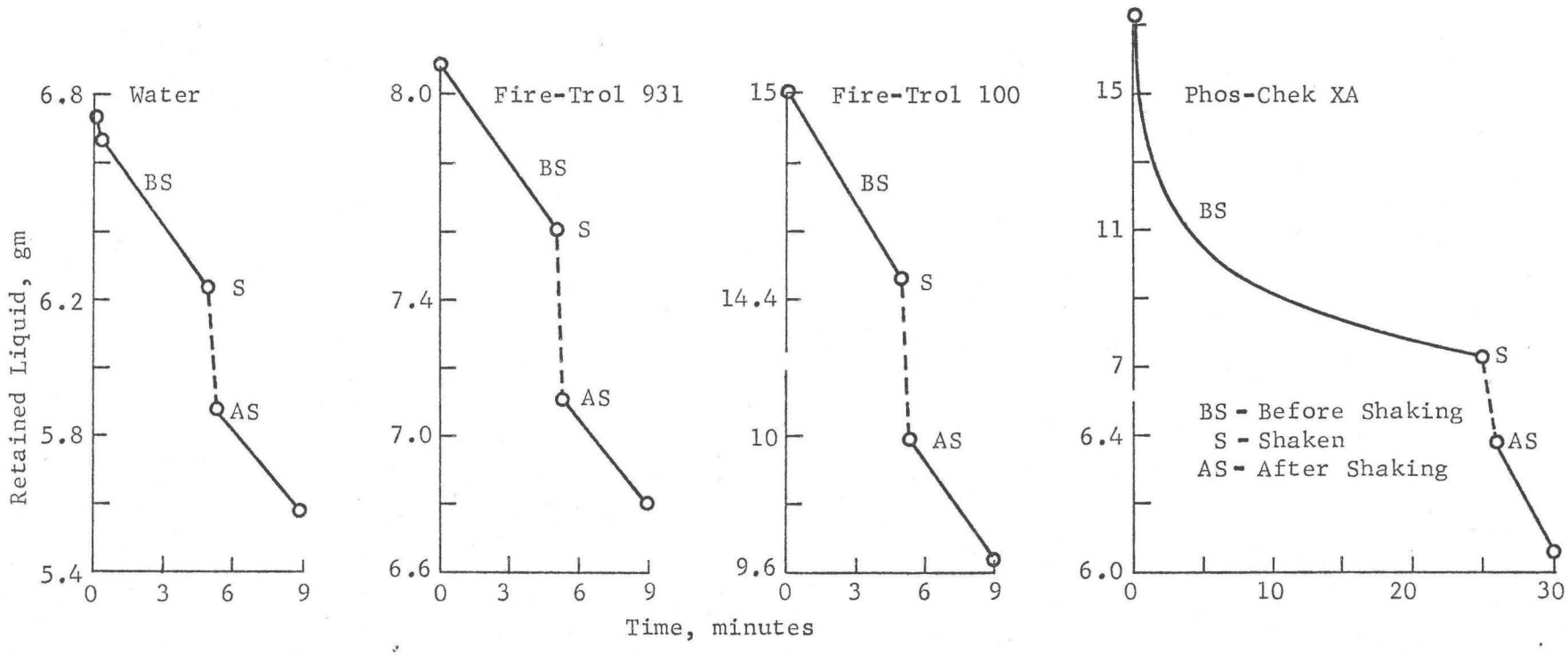


Figure 38. Measured Weight History of the Retardants on the Middle Tree Section. The Straight Lines Represent Evaporation; the Curved Line Represents Dripping Plus Evaporation.

TABLE VIII. MEASURED MAXIMUM STABLE LIQUID FILM THICKNESS ON THE DOWEL TREE

Fluid	Initial Film Thickness cm	Film Thickness After Shaking cm
Water	0.077	0.067
Fire-Trol 931	0.093	0.080
Fire-Trol 100	0.165	0.111
Phos-Chek XA	0.088*	0.076

* Approximate, see the discussion.

Phos-Chek XA differed from the other fluids in that it dripped continually off of the tree section after the immersion. The resulting weight loss curve (Figure 38) of the liquid was nonlinear and represents simultaneous dripping and evaporation. Although the dripping slowed down greatly with time, it was difficult to obtain an exact value for the stable retained liquid since the dripping from the various branches was not all the same (the liquid on some branches would become stable and thereafter continue to evaporate, while some branches still dripped slowly). An approximate value of 7.7 gms was selected as the weight of the stable retained liquid but this value is subject to some uncertainty. The corresponding film thickness is given in the table. After shaking the averaged retained weight was 6.638 gm.

A comparison of the film thickness of the fluids in Table VIII with those in Figure 33, 35 and 37 indicates that at large recovered volumes the values in the figures exceeds those in the table for water, Fire-Trol 931 and Phos-Chek XA. Moreover, not all the dowel area was covered with liquid in most of these cases. The difference is believed due to absorption of liquid by the dowel over the relatively long time period required to conduct the experiment (the dipping experiments required only a very short time to make the initial measurements). An inspection of the dowels revealed that they did indeed absorb liquid, with water being most readily absorbed.

4.3 WETTING CHARACTERISTICS OF THE POLYETHYLENE DOWEL TREE

In order to obtain further information regarding the effects of fuel composition and surface properties on the wetting-out process, experiments were also conducted using dowel trees made from polyethylene. The basic tree was made in the same manner as (and was identical to) the birch dowel tree discussed in section 4.1 and shown in Figure 28, except that it (both the stock and branches) was made from smooth polyethylene plastic. Medium sized (4-5mm) drops of the retardants were used in the studies. Two experiments were conducted with Fire-Trol 100, and one experiment each on the other three retardants.

4.3.1 General Wetting Behavior and Liquid Recovery

The general mechanism of the wetting out of the birch dowel tree by falling liquid drops described earlier (section 4.2.1, 4.2.2) was also found to occur for the polyethylene dowel tree. Moreover the general behavior of the retardants regarding impact splatter, run and drip on the wetting of the birch tree also apply to the polyethylene

tree. However there was one significant difference between the behavior of the retardants on the two different composition dowel trees, and this had a significant effect on the retention of the liquid on the tree and the average film thickness. As discussed in Section 3, the impact of a single drop of retardant on a polyethylene dowel caused the liquid to spread over the dowel surface, and simultaneously some ejected splatter was produced (at large drop heights). The liquid retained on the dowel was a function of the surface area covered by liquid, which was larger for smooth polyethylene than for birch. A short time after the impact (several seconds or more) the spread liquid contracted into ligaments, threads and beads which nevertheless were still retained on the dowel.

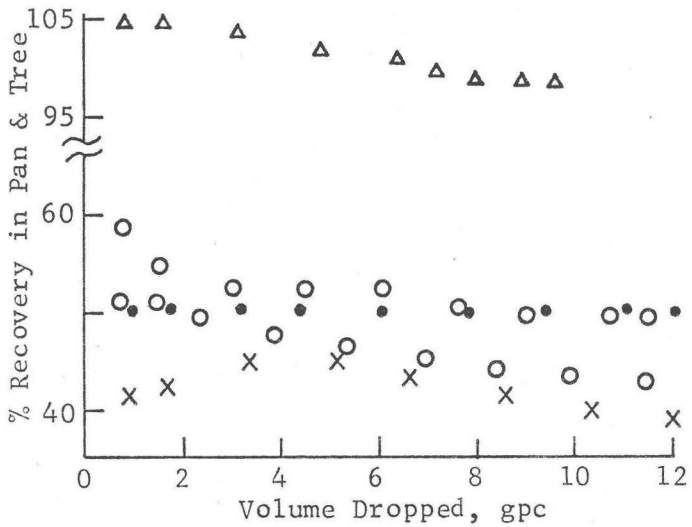
This general behavior of the various liquid (except for Fire-Trol 100) likewise occured during the wetting of the polyethylene dowel tree (for water the contraction was very fast). However in these cases since liquid drops were continually being dropped on the tree, the contracted liquid quickly enlarged into hanging drops on the branches, which broke to give downward drip. Liquid on the stock rapidly developed into stemflow. The result was that the initially retained liquid on the polyethylene tree was not stable, and a larger fraction of the liquid was eventually lost to the ground (the pan) than in the case of the birch tree. The general effect was especially pronounced for water, and occurred to a lesser extent for Fire-Trol 931 and Phos-Chek XA in that order.

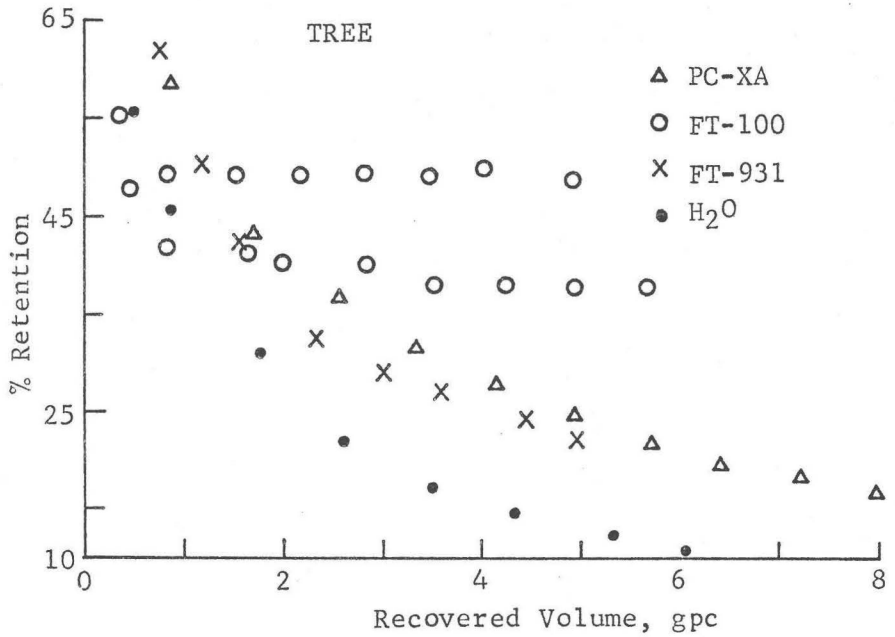
On the other hand the impact splotches of Fire-Trol 100 on the polyethylene tree were considerably more stable, and had a much smaller tendency to breakup. Moreover the splotches had a tendency to dryout to some degree (in some cases completely where no secondary impacts occurred for some time), which stabilized them with respect to contractive breakup and drip. Consequently the fluid retention and film thickness of Fire-Trol 100 were significantly larger than for the other fluids, especially at the larger (and important) values of recovered liquid volume.

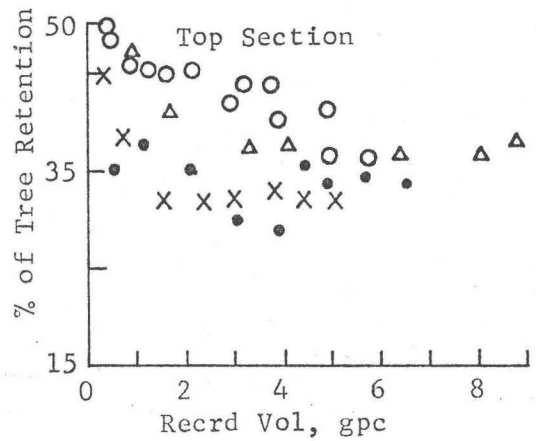
The fractional recovery of the liquid in the experiments is given in Figure 39. Essentially all of the Phos-Chek XA was recovered, and about half of the other retardants. The relative ordering of the latter retardants differs from that obtained with the birch dowel. (Figure 29).

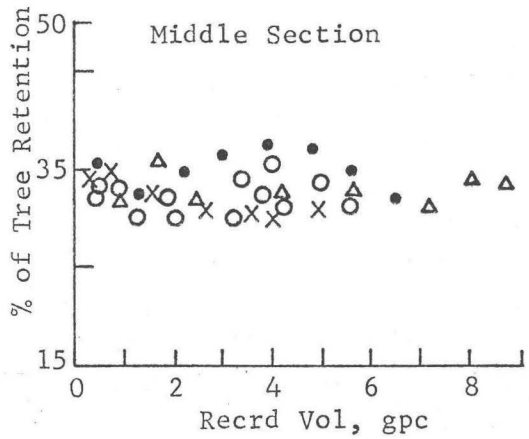
4.3.2 Liquid Retention and Film Thickness

The percentage of the recovered liquids retained on the tree and its sections is shown in Figure 39. Fire-Trol 100 had the greatest fractional retention in the top section of the tree, and consequently the smallest retention in the bottom section. The fraction of the retained liquid decreased with increasing fluid volume in the top section, and increased in the bottom section. On the other hand, Fire-Trol 931 had the smallest retention in the top section of the tree, and the largest in the bottom section. This ordering of the Fire-Trol fluids is opposite to that obtained for the birch tree (Figure 29). The retention of the various fluids was generally largest in the top section of the tree and smallest in the bottom section, as found before. In the case of the tree as a whole, Fire-Trol 100 had the largest fractional retention, except at small fluid volumes. The retention of Fire-Trol 100 was independent of fluid volume; whereas that of the other fluids decreased with increasing volume. Water generally had the smallest fractional retention of all the fluids.









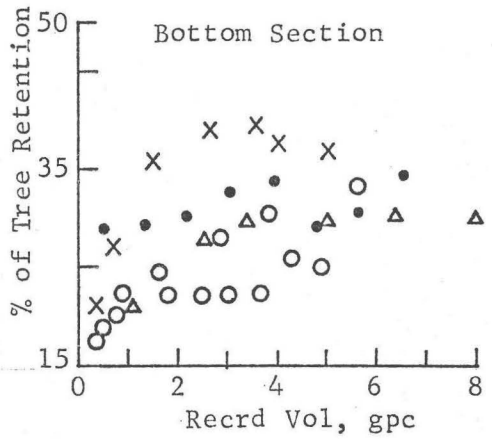


Figure 39. Experimental Retention of the Impacted Liquids (4-5 mm Drops) on the Smooth Polyethylene Dowel Tree and Its Individual Sections.

The average film thickness of the retardants on the smooth polyethylene tree is shown in Figure 40. Fire-Trol 100 had the greatest thickness on all three sections of the tree and the tree as a whole, except at small recovered liquid volumes where all the retardants were about the same. The film thickness increased with increasing fluid volume, as in the previous cases. On the other hand, water had the smallest film thickness on the tree and all its sections, and its average thickness was constant and independent of volume at recovered volumes greater than about 1-2 gpc. The film thickness of Phos-Chek XA was generally greater than that of Fire-Trol 931 on the tree and its various sections, and the film thickness vs recovered volume curves are nonlinear. These general behaviors of the retardants differ significantly from those obtained on the birch tree. The film thickness on the polyethylene tree and its sections correlate roughly with the apparent viscosity of the fluids at low shear rates (Table III), i.e., higher apparent viscosity fluids have greater film thickness. This may result because the bonding between the various fluids (except Fire-Trol 100) and the polyethylene is relatively weak so that the ease of liquid flow becomes of more importance in the retention of liquid on the tree. This correlation was not observed on the birch tree because of the ability of the liquids to stick to the tree.

4.3.3 Effect of Surface Roughness

In order to determine the effect of surface roughness on the liquid wetting and retention process, experiments were conducted using a roughened polyethylene dowel tree. The dowel tree was identical to that used in the studies just described, except for a roughening of its limb dowels (the stock was left smooth). The limbs were roughened by cutting eight horizontal straight grooves about 0.002 in. deep (approximately equally spaced) on the surface of each limb dowel, using a lathe with a blade. This was followed by series of 0.02 in. deep spiral grooves spaced 0.05 in. apart, threaded on each dowel with a die. A checkered surface pattern was thus produced on the limbs. The threading process resulted in the formation of very small polyethylene fibers being produced permanently on the dowel surface. One test was conducted for each fluid, the tree being washed and dried between tests, the same as for the smooth polyethylene tree. Medium sized (4-5mm) drops of retardants were used in the tests.

4.3.3.1 Wetting Behavior and Liquid Recovery

The impact of liquid drops with the dowel tree generally caused the parent drop to be broken up into several fragments that remained on the roughened surface, as well producing side splatter. For water the surface fragments generally consisted of several small fragments; for the other fluids the fragments consisted of one main fragment, with several very small fragments on each side of the main fragment. Except for the difference in the nature of the initially impacted liquid, however, the general mechanism of wetting appeared to be the same as for the smooth tree.

Figure 41 shows the recovery of the dropped liquid. The recovery of the Phos-Chek XA was a little lower than with the smooth

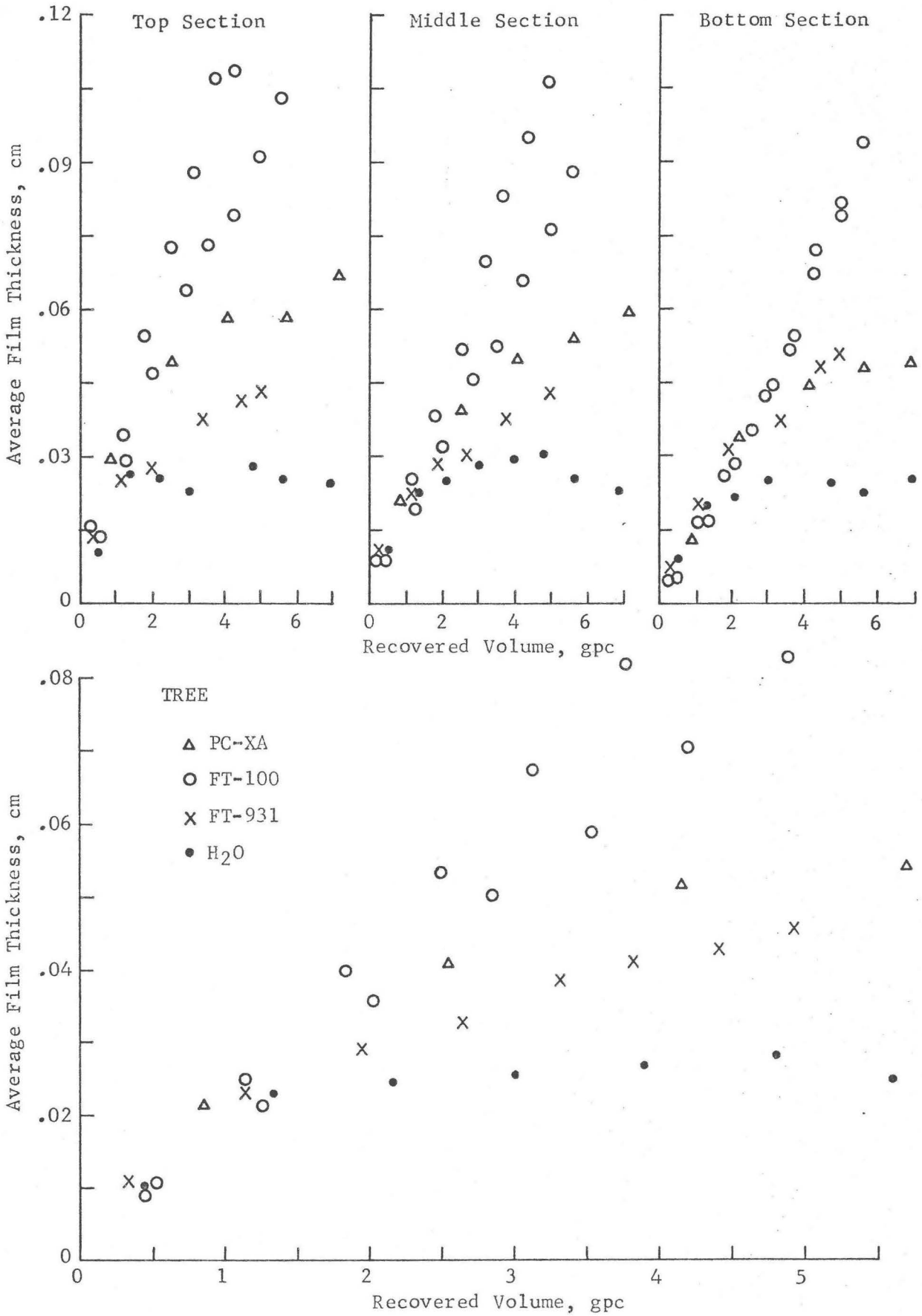


Figure 40. Average Film Thickness of the Retained Liquid (4-5 mm Drops) on the Smooth Polyethylene Dowel Tree and Its Individual Sections.

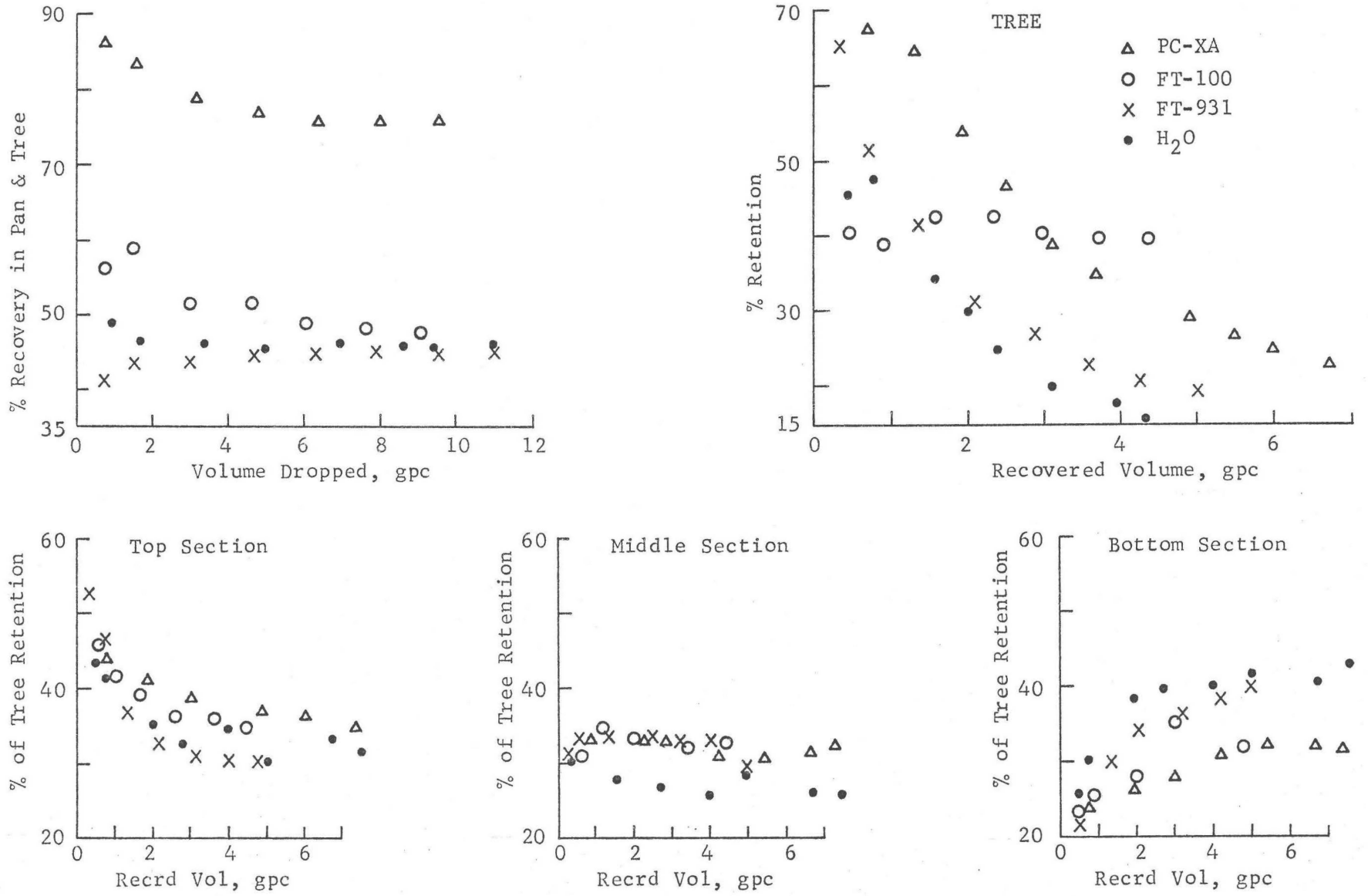


Figure 41. Experimental Retention of the Impacted Liquids (4-5 mm Drops) on the Roughened Polyethylene Dowel Tree and Its Individual Sections.

polyethylene tree, but otherwise the general recovery of the various liquids was about the same.

4.3.3.2 Liquid Retention and Film Thickness

The retention of the liquid in the tree and its sections is also shown in Figure 41. The retention of water and Fire-Trol 931 were the smallest in the top section, and largest in the bottom section, as was also the case for the smooth tree. The general ordering of the fluids for the whole tree as well as its individual sections was about the same as for the smooth tree, indicating that liquid flow (drip) and fluid viscosity are of special importance.

The average film thickness of the retained liquid on the roughened polyethylene tree is shown in Figure 42. The general relative ordering of the fluids with respect to film thickness was the same as for the smooth polyethylene tree for both the tree and its sections, i.e., Fire-Trol 100 had the largest film thickness followed by Phos-Chek XA, Fire-Trol 931 and water, in that order. Thus film thickness increased with increasing apparant fluid viscosity (the low shear rate values).

The general behavior of the film thickness vs recovered fluid volume curves are also the same for the smooth and roughened trees, as are the magnitudes of the film thickness and liquid retention for the two trees. Some dipping experiments were conducted, and it was found that in this (static) case the roughened polyethylene retained more of the various retardants than the smooth polyethylene. On the other hand, dropping single drops of retardant from about 2 ft, drop height resulted in greater retention of the liquids on the smooth dowel. This could be due to the circular (spiral) nature of the deeper grooves on the surface, which would tend to channel liquid off the surface of the dowel.

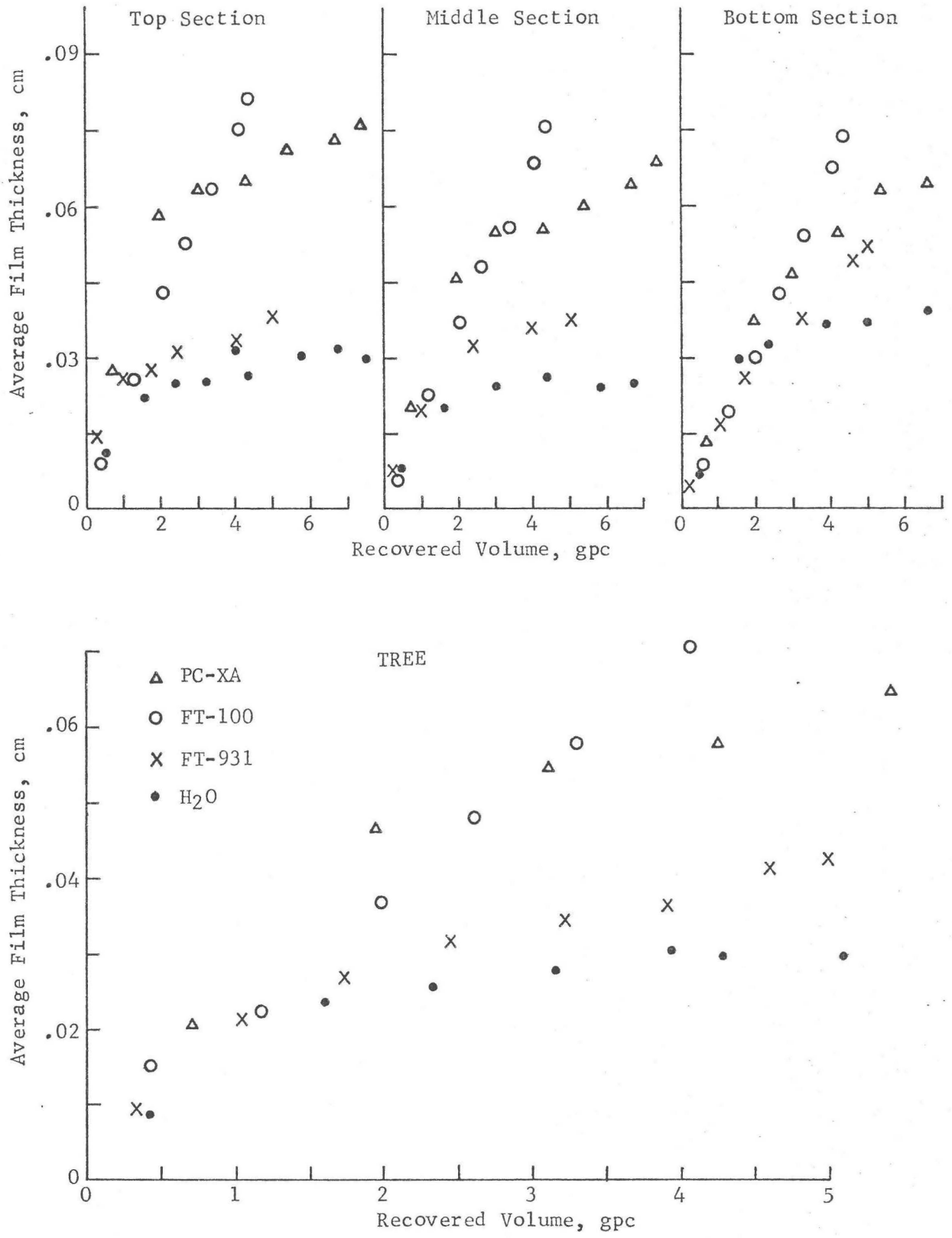


Figure 42. Average Film Thickness of the Retained Liquid (4-5 mm Drops) on the Roughened Polyethylene Dowel Tree and Its Individual Sections.

5. RETARDANT WETTING OF REAL FUEL STRUCTURES

Subsequent to the experiments with simulated fuel structures just described, similar studies were conducted with real fuel structures in order to determine what differences are introduced by the real structure's surface details. The initial studies were conducted on fuel structures with the same general geometry as the simulated fuel structures just described, i.e., the real fuel structures were assembled in the form of the basic dowel tree discussed in the previous section. The dowel trees in this case were fabricated using:

(1) branches made from green willows (twigs) with bark,
(2) branches wrapped with waxy leaves, and
(3) branches made from twig elements with pine needles.

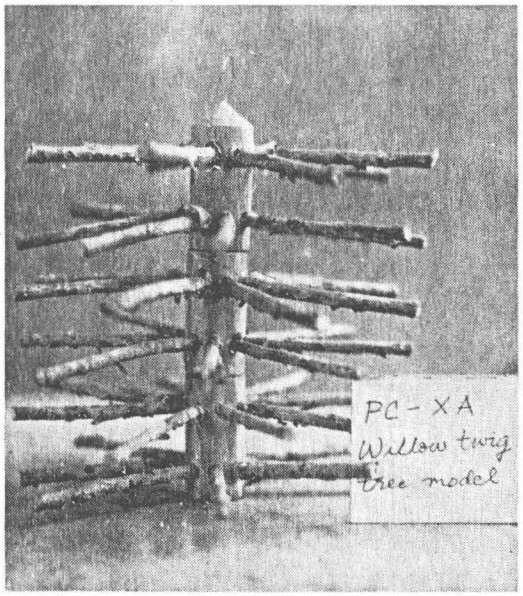
After these studies, similar wetting experiments were made on a natural real-fuel structure (Juniper Tam).

5.1 WETTING CHARACTERISTICS OF TWIGS WITH BARK

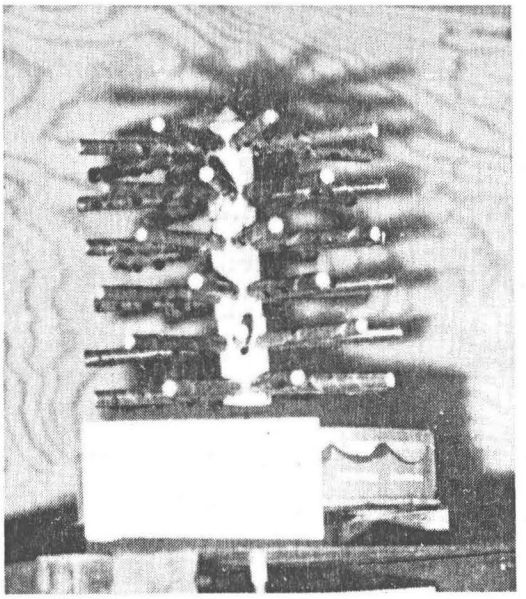
In order to study the wetting characteristics of twigs with bark, experiments were conducted on a dowel tree made up of freshly cut smooth green willows. The tree had the same geometry, design and dimensions as the basic dowel tree discussed in section 4.1, and differed from the birch dowel tree essentially only in that the limbs were made from the willows. The diameter of the willows was kept as close to that of the birch and polyethylene limbs (0.25 in.) as possible, but there were some small variations due to the difficulty in finding uniform willows with the exact desired diameter. Generally speaking the variation in diameter (from 0.25 in.) was about $\pm$ 0.05 in. The limbs were generally mostly smooth, but in some cases it was necessary to cut off small secondary branches that were present, and the bark was thus broken at these sites. The limbs were inserted into a birch stock (cut into three sections), as used for the birch dowel trees. The stock was coated with a layer of Duco cement to give a shiny and waxy texture, somewhat like that of the limbs. The general appearance of the green willow dowel tree is shown in Figure 43 (this picture was taken several days after the experiment, and consequently the liquid has dried and the limbs shrunken somewhat).

5.1.1 General Wetting Behavior and Liquid Recovery

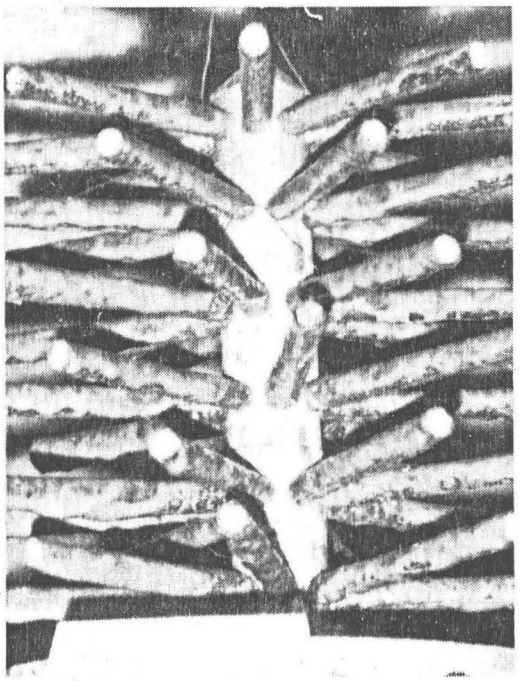
The experiments were conducted using medium sized (4-5mm) drops of the various retardants and also large (7mm) drops of Phos-Chek XA (one experiment each case). The general impact behavior of the liquid drops with the willow bark surface was essentially similar to that for the roughened polyethylene. The impacting drop first spread on the surface and (except for Phos-Chek XA) produced significant side splatter. In the case of water and Fire-Trol 931, the spreading film then broke up into a number of small drops and ligaments, whose concentration was greatest near the spreading periphery. For Fire-Trol 100 and Phos-Chek XA however the film did not break up, and the impact pattern consisted of a main central splotch surrounded by a few very small drops. As the dropping of the liquids continued and the localized liquid levels increased, hanging drops formed and broke to give downward drip. The



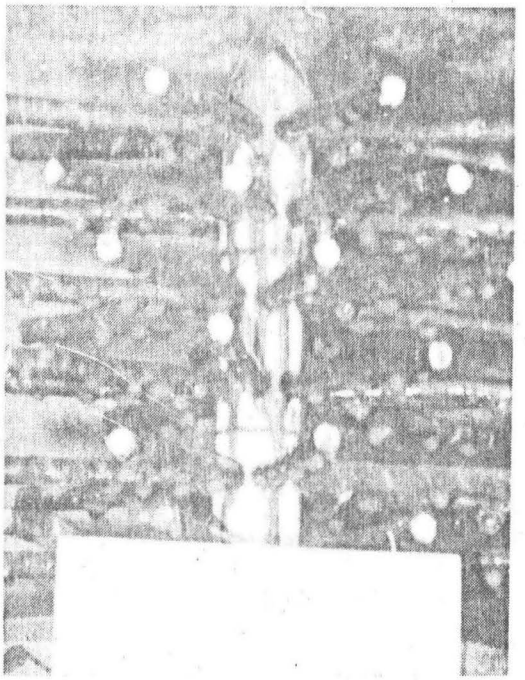
Willow Twig (After Drying)



Rolled Leaf Tree, H_2O 5 gpc



Rolled Leaf Tree, FT-100 5 gpc



Rolled Leaf Tree, PC-XA 8 gpc

Figure 43. General Appearance of the Green Willow Branch and Rolled Ivy Leaf Dowel Trees.

general dripping behavior was similar to the previous cases in that Phos-Chek XA dripped most extensively; whereas Fire-Trol 100 scarcely gave any drip. The relative role of side splatter on the wetting process, and the general behavior of the stem flow was also similar.

The experimental recovery of the dropped liquids in the tree and drip pan is shown in Figure 44. The recovery of the Phos-Chek XA (both drop sizes) was greatest, and the other liquids were lower and about the same. The recovery characteristics are quite similar to those on the roughened polyethylene tree (Figure 41).

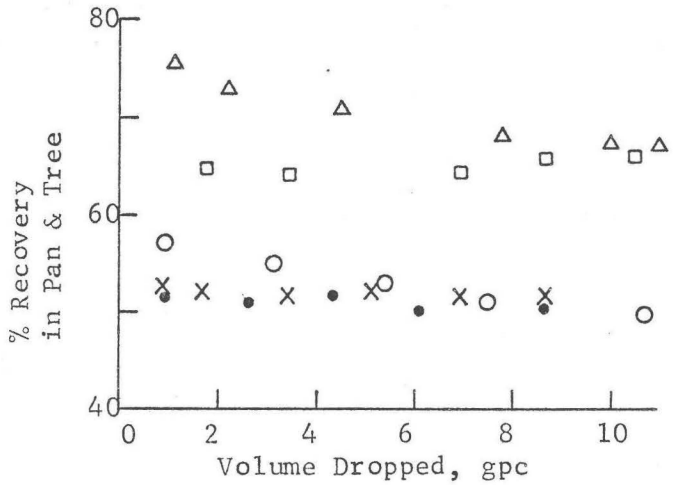
5.1.2 Liquid Retention and Film Thickness

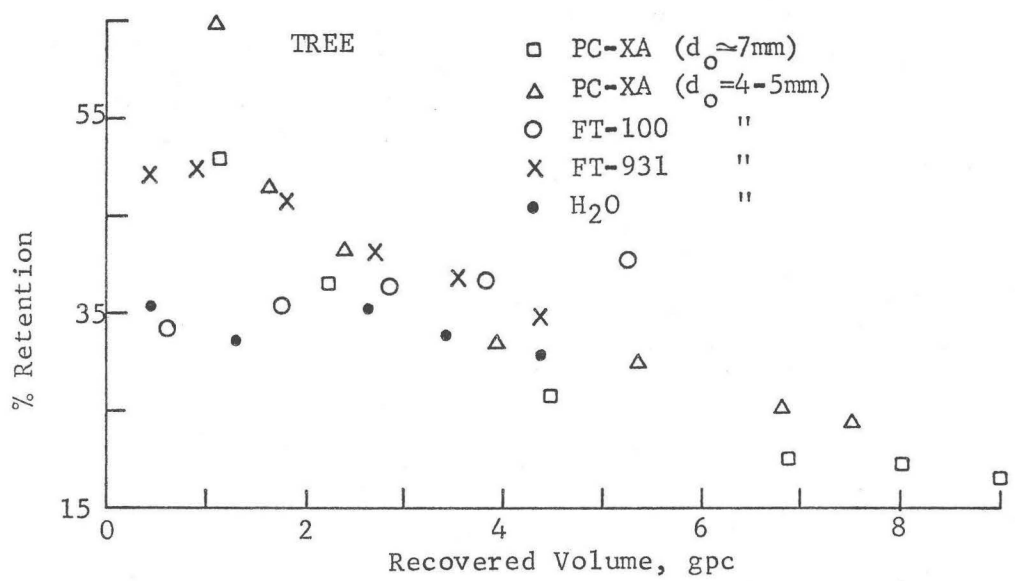
The percentage of the recovered liquid that was retained in the tree and its individual sections is also shown in Figure 44. The general retention characteristics and relative ordering of the fluids on the tree and its three individual sections are quite similar to those on the roughened polyethylene tree, although there are some small differences. The retention of the various liquids at small recovered volumes was greatest in the top section of the tree, followed by the middle and bottom sections, as before, but at large volumes the retentions tended to equalize.

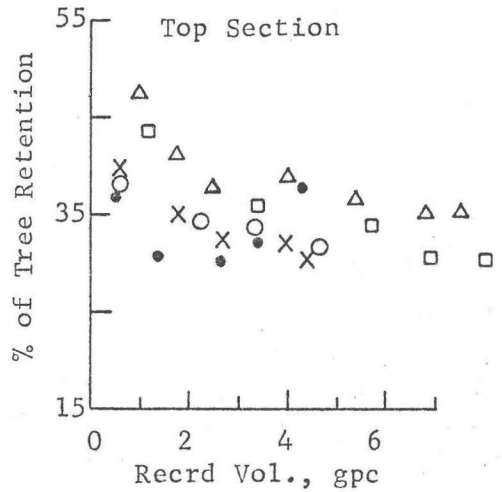
Figure 45 shows the average film thickness of the retained liquid on the tree and its sections. The relative ordering of the fluids is quite similar to the ordering on the roughened polyethylene tree, but the film thickness of water and Fire-Trol 931 is significantly larger at large fluid volumes and increases with increase in volume rather than tending to become constant. It is also of interest that the medium size drops of Phos-Chek XA produce a greater film thickness than the large drops, especially at the higher recovered fluid volumes. In computing the film thickness in this figure it was assumed that the surface area of the green willow tree was the same as that of the birch and polyethylene tree dowels (263.47 cm^2; and each section 87.82 cm^2). However since the diameter of the various limbs sometimes differed a little from 0.25 in. (as discussed before), the true surface area of the various trees may have differed from the assumed value. Hence the computed average film thicknesses should be considered approximate in nature in comparing them with the birch and polyethylene tree dowel results.

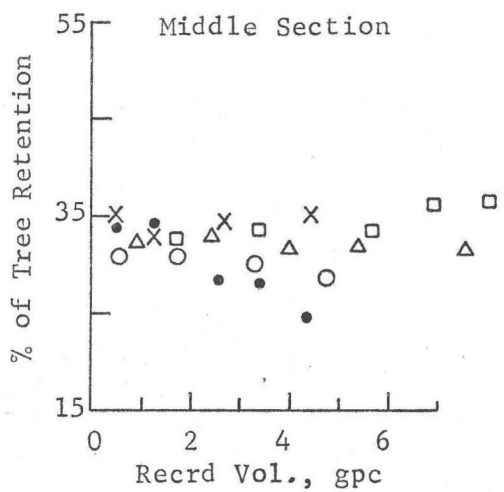
5.2 WETTING CHARACTERISTICS OF A STRUCTURE WITH WAXY LEAVES

In order to study the wetting characteristics of structures with waxy leaves, experiments were conducted on the basic birch dowel tree in which each limb (all 48) was wrapped with a fresh green ivy leaf. The leaves were cut into approximately 0.8 in. x 3 in. rectangular sheets, which were wrapped around the surface of the limb dowel using double-stick tape. The cross sectional ends of the dowel were left unwrapped, and the ends of the leaf overlapped slightly at the joint when the limb was inserted into the hub. The green side of the leaf was facing out, and the taped edge was placed in the bottom position. The stock of the tree was not wrapped with leaves, but was coated with a layer of Duco cement to give a shiny and waxy texture as for the willow tree dowel. The general appearance of the tree dowel wrapped with greenivy leaves is shown in Figure 43.









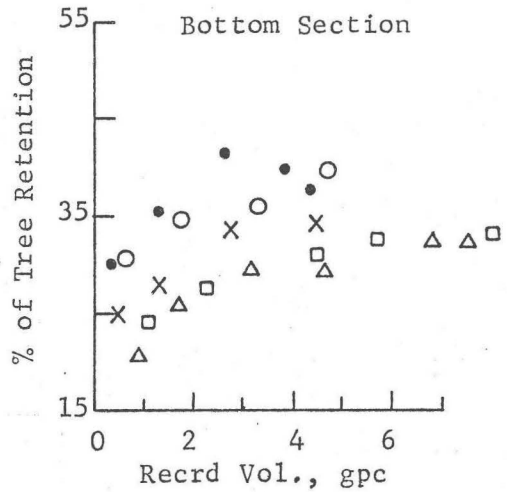


Figure 44. Experimental Retention of the Impacted Liquids on the Green Willow Dowel Tree.

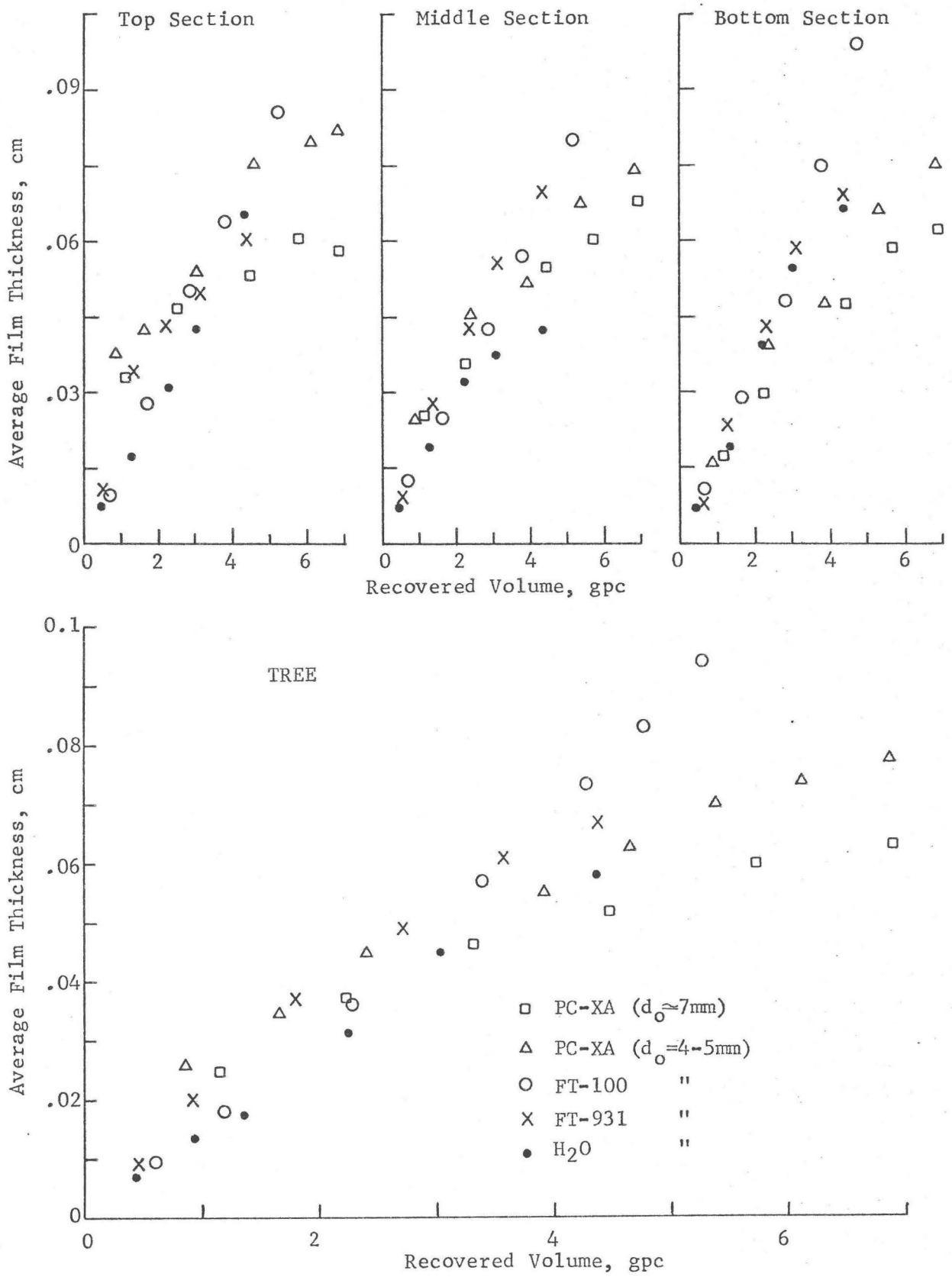


Figure 45. Approximate Average Film Thickness of the Retained Liquid on the Green Willow Dowel Tree.

5.2.1 General Wetting Behavior and Liquid Recovery

The general behavior of the impacting drops with the fixed leaf surface was essentially the same as for the green willow limbs, and the general wetting behaviors of the fluids including the roles of splatter, drip and run were also the same.

Figure 46 shows the recovery of the dropped liquid in the dowel tree and drip pan using medium sized (4-5mm) drops of the four retardants (one experiment for each fluid). As in all previous cases, the recovery was greatest for Phos-Chek XA. The general characteristics of the fluid recovery was quite similar to that for the roughened polyethylene and green willow dowel trees.

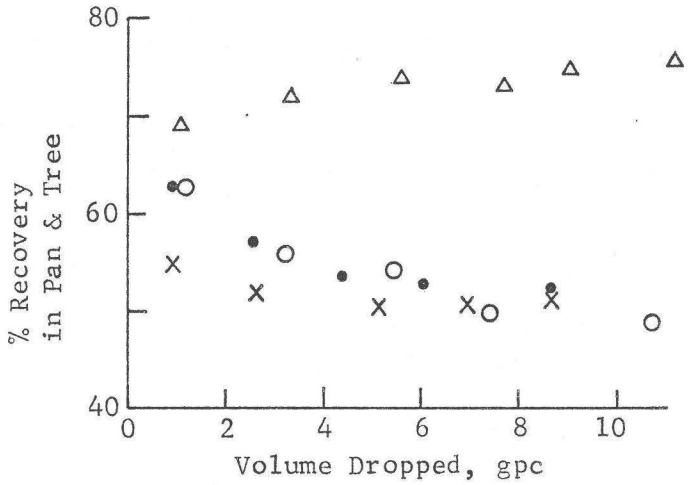
5.2.2 Liquid Retention and Film Thickness

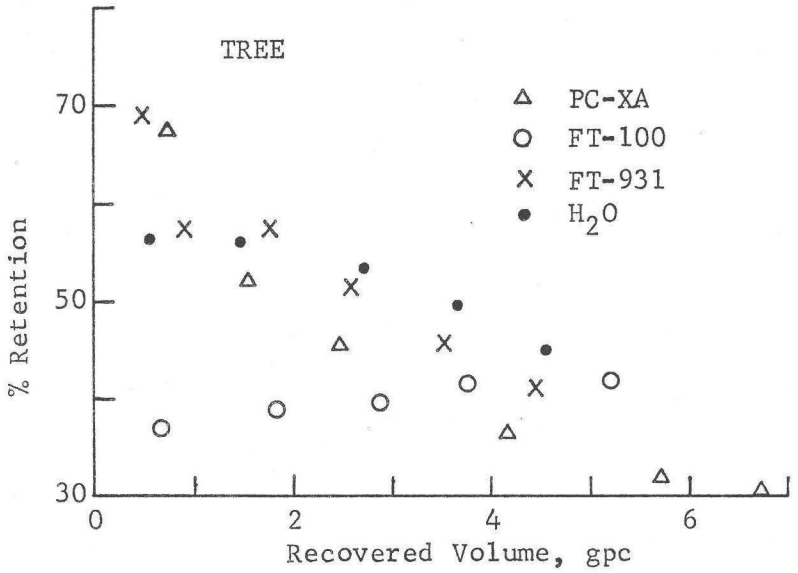
The percentage of the recovered liquid that was retained in the tree and its individual sections is also shown in Figure 46. Phos-Chek XA had the highest retention in the top section of the tree and the lowest in the bottom section; whereas the retention of Fire-Trol 100 was just opposite. The retention characteristics of Phos-Chek XA were essentially the same as for the green willow tree. In general the top section of the tree had the largest retention of all the fluids (with the possible exception of Fire-Trol 100), followed by the middle and bottom sections. The fluid retention in the tree as a whole was smallest for Fire-Trol 100 (except at very large fluid volumes). The fractional retention of Fire-Trol 100 was essentially independent of volume; whereas the retention of the other fluids decreased with increasing volume.

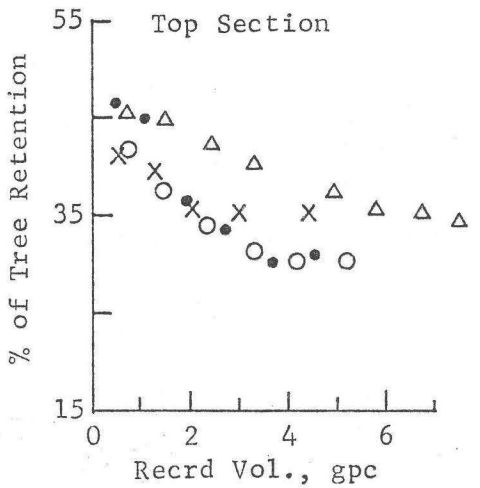
The average film thickness of the retained liquid on the dowel trees wrapped with green ivy leaves is shown in Figure 47 (the area used in the computations was that of the birch tree and its sections, and the film thicknesses are thus approximate). The film thickness of Fire-Trol 100 was the smallest of all the fluids in the top and middle sections of the tree, and also the entire tree, except at very high recovered volumes when it eventually became largest (due to its retention vs fluid volume characteristics). Water and Fire-Trol 931 had the largest film thickness, although at the smaller fluid volumes Phos-Chek XA was also about the same. (Note that the film thickness plots do not necessarily correlate directly with the percentage retention curves because of the gpc factor in converting fluid retention to film thickness, Eq. (3)).

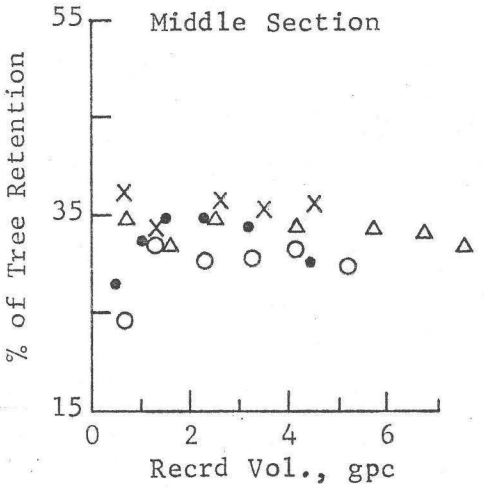
5.2.3 Effect of Drop Size

Tests were also conducted using small (2mm) drops of water and Fire-Trol 931, and large (7mm) drops of Phos-Chek XA. The liquid recovery and tree retention curves are shown in Figure 48. Phos-Chek XA had the greatest recovery as usual, and water was greater than Fire-Trol 931. The retention of the fluids with small drops increased a little in the top section of the tree at low recovered fluid volumes, but otherwise the liquids retained in the tree did not differ appreciably from that of the medium sized drops. The average film thickness of the retained liquids is shown in Figure 49. It may be seen that the thickness and its characteristics are roughly the same as obtained for the medium sized drops (Figure 47). Thus it would appear that droplet size had little effect on the overall









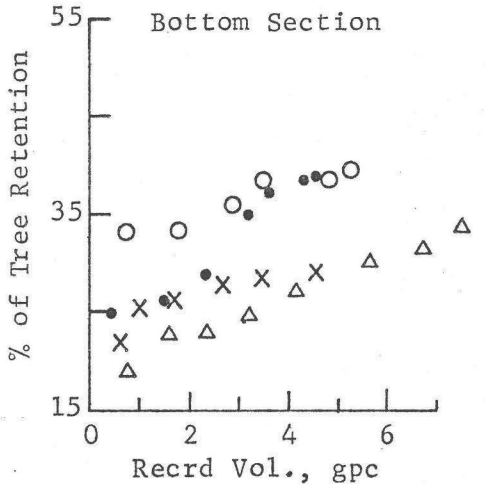
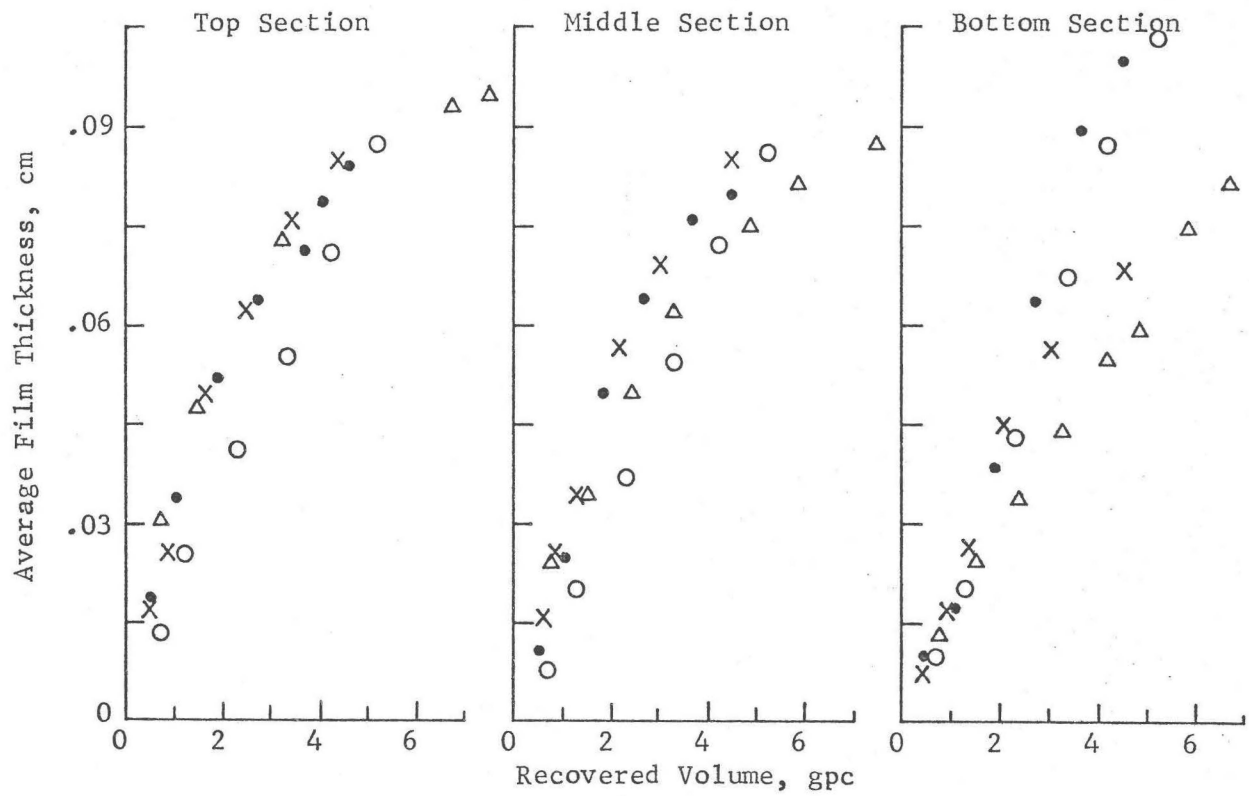


Figure 46. Experimental Retention of the Impacted Liquids (4-5mm Drops) on the Dowel Tree Wrapped with Green Ivy Leaves.



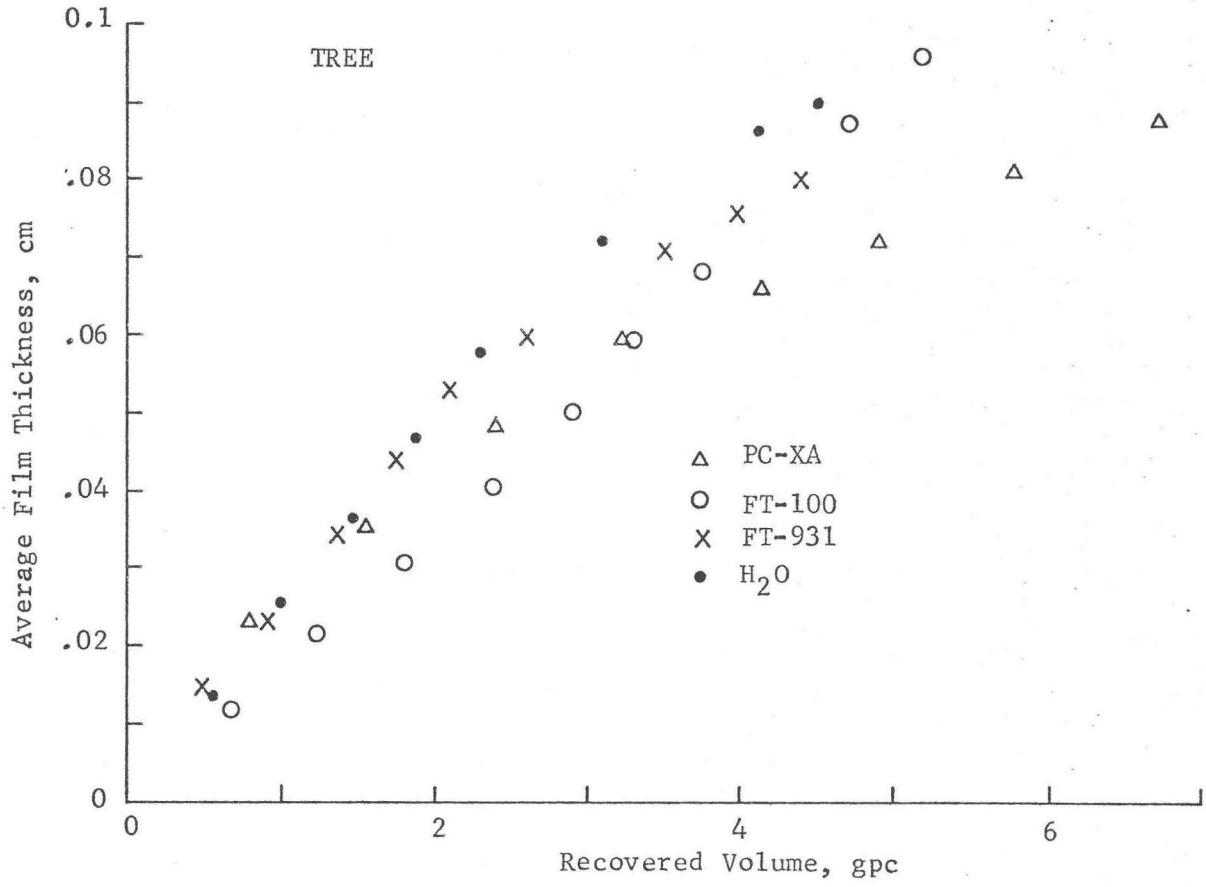


Figure 47. Approximate Average Film Thickness of the Retained Liquid (4-5mm Drops) on the Dowel Tree Wrapped with Green Ivy Leaves.

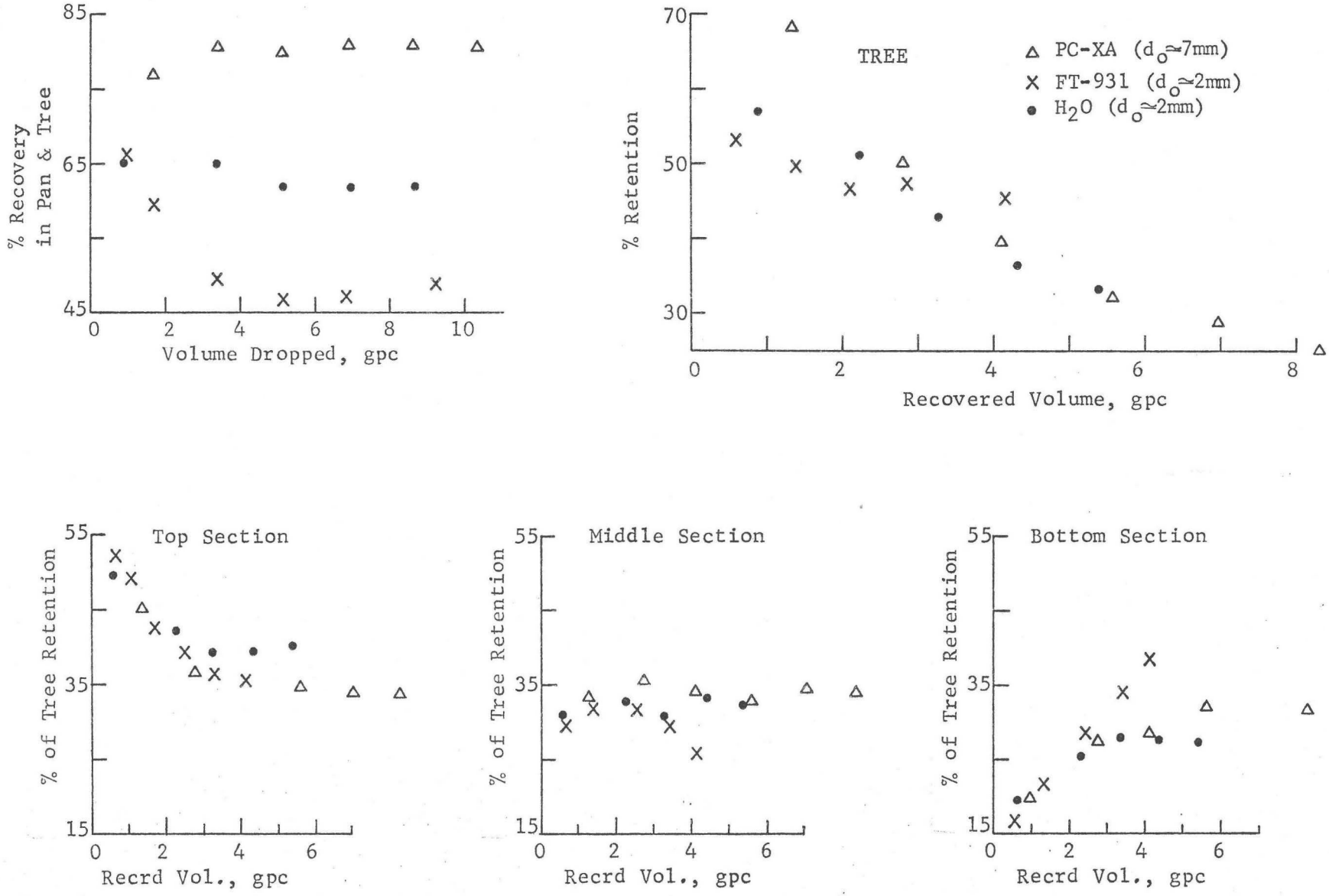


Figure 48. Experimental Retention of the Impacted Liquids (Small and Large Drops) on the Dowel Tree Wrapped With Green Ivy Leaves.

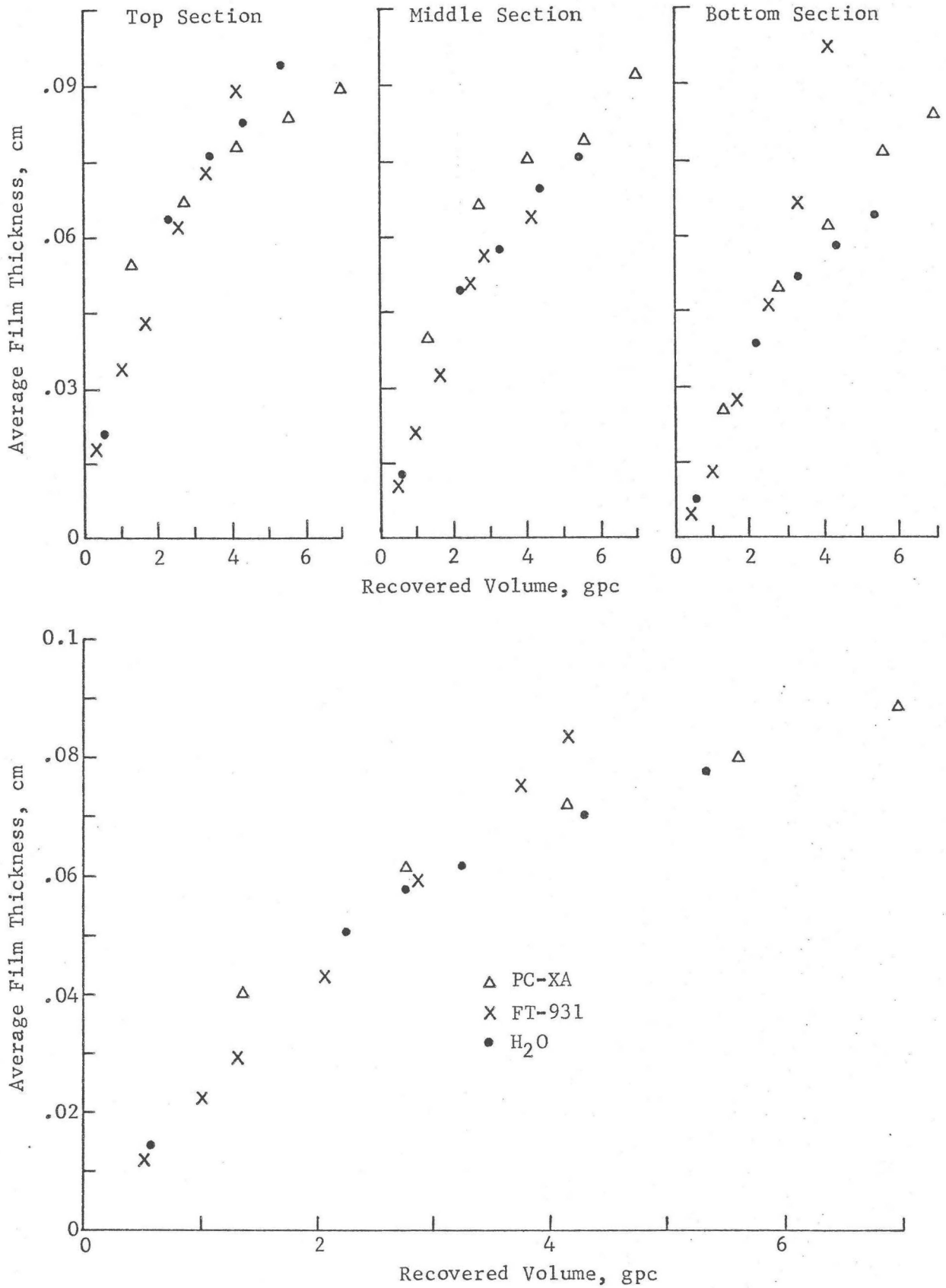


Figure 49. Approximate Average Film Thickness of the Retained Liquid (Small and Large Drops) on the Dowel Tree Wrapped With Green Ivy Leaves.

wetting out of the dowel tree wrapped with green ivy leaves.

5.3 WETTING CHARACTERISTICS OF A STRUCTURE WITH NEEDLES

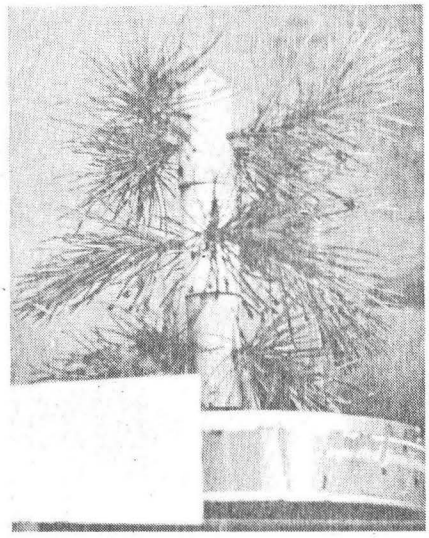
In order to study the wetting characteristics of structures with needles, experiments were conducted on small trees containing clusters of pine needles. The trees were constructed using the same stock (three detachable sections) used for the birch dowel tree. At the middle of each section (hub), four 1/8 in. diam. holes (1/4 in. deep) were bored on the four opposing sides, and a cluster of fresh pine needles inserted. These clusters were about 3 in. in length, and were cut from a Ponderosa pine branch. There were thus 12 clusters of needles on each tree, and the clusters in each section were rotated with respect to one another to minimize the free space available to a falling drop. Different trees were used for different tests, and therefore were not exactly identical as in the case of the previous model trees or tree dowels (the individual sections of the trees also could differ). Figure 50 illustrates the trees used in the studies. In some cases the ends of the twigs (holding a needle cluster) had to be taped so they would hang tight and horizontal on the hub. Occasionally the pine needles were trimmed so that the needles from one cluster did not crossover or overlap with the ones from the other clusters.

5.3.1 General Wetting Behavior

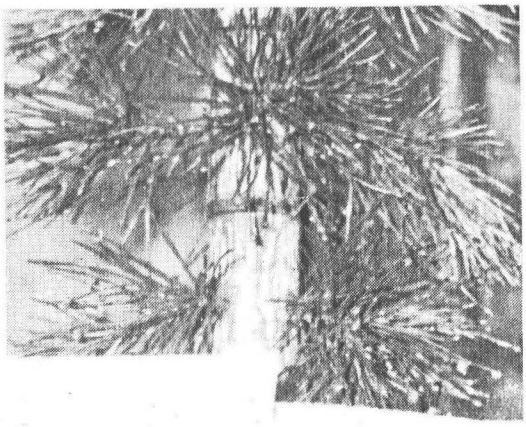
The impact of the falling drops with the pine needle clusters resulted in side splatter, run and drip as in the previous cases, but there were some differences. Impacting drops of Fire-Trol 931 left more of a compact stain (film) on the impact site than water, and the initial coatings from Fire-Trol 100 and Phos-Chek XA were even thicker. Water, Fire-Trol 931 and Phos-Chek XA ran readily along vertically-oriented needles to give very small hanging drops (smaller than those in the other tests) at the needle tips, and subsequent downward drip (Fire-Trol 100 had a very small drip only after dropping a large fluid volume). The dripping was most pronounced for water, while simultaneous film coverage of the needles occurred with Fire-Trol 931 and Phos-Chek XA. The dripping occurred most extensively on the bottom section of the tree for water and Fire-Trol 931, followed by the middle and top sections; while for Phos-Chek XA the top section seemed to drip the most. Dripping also occurred from the sides of twigs where drop impact occurred, especially for Phos-Chek XA, and side splatter contributed to the wetting of the tree (Phos-Chek XA had less splatter than the other fluids). In general the liquid coating of the twigs where the needles grew out of was more pronounced than the coating of the needles. In some cases for Fire-Trol 100, localized regions became so saturated that the needles would be held together by the thick fluid (Figure 50). Also for this fluid, localized spots on the needles would dry up when they weren't further coated for awhile as the result of subsequent falling drips (by impact or splatter).

5.3.2 Liquid Recovery and Retention on the Structure

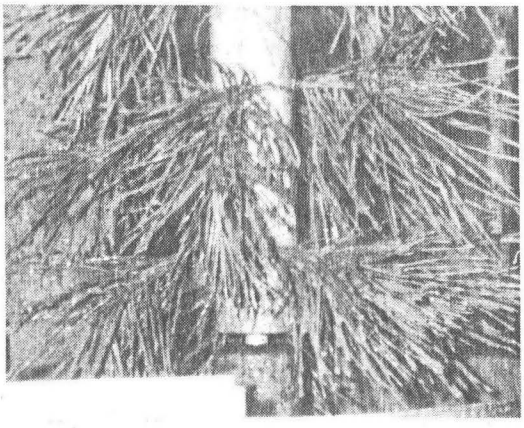
The experiments were conducted using medium sized (4-5mm) drops of the various fluids, and also large (7 mm) drops of Phos-Chek XA (one test each). Figure 51 shows the recovery of the liquid in the



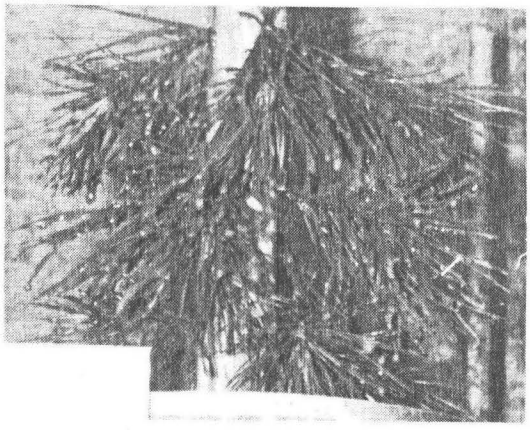
H_2O 5 gpc



FT-931 5 gpc



FT-100 5 gpc



PC-XA 10 gpc

Figure 50. General Appearance of the Pine Needle Tree Structures.

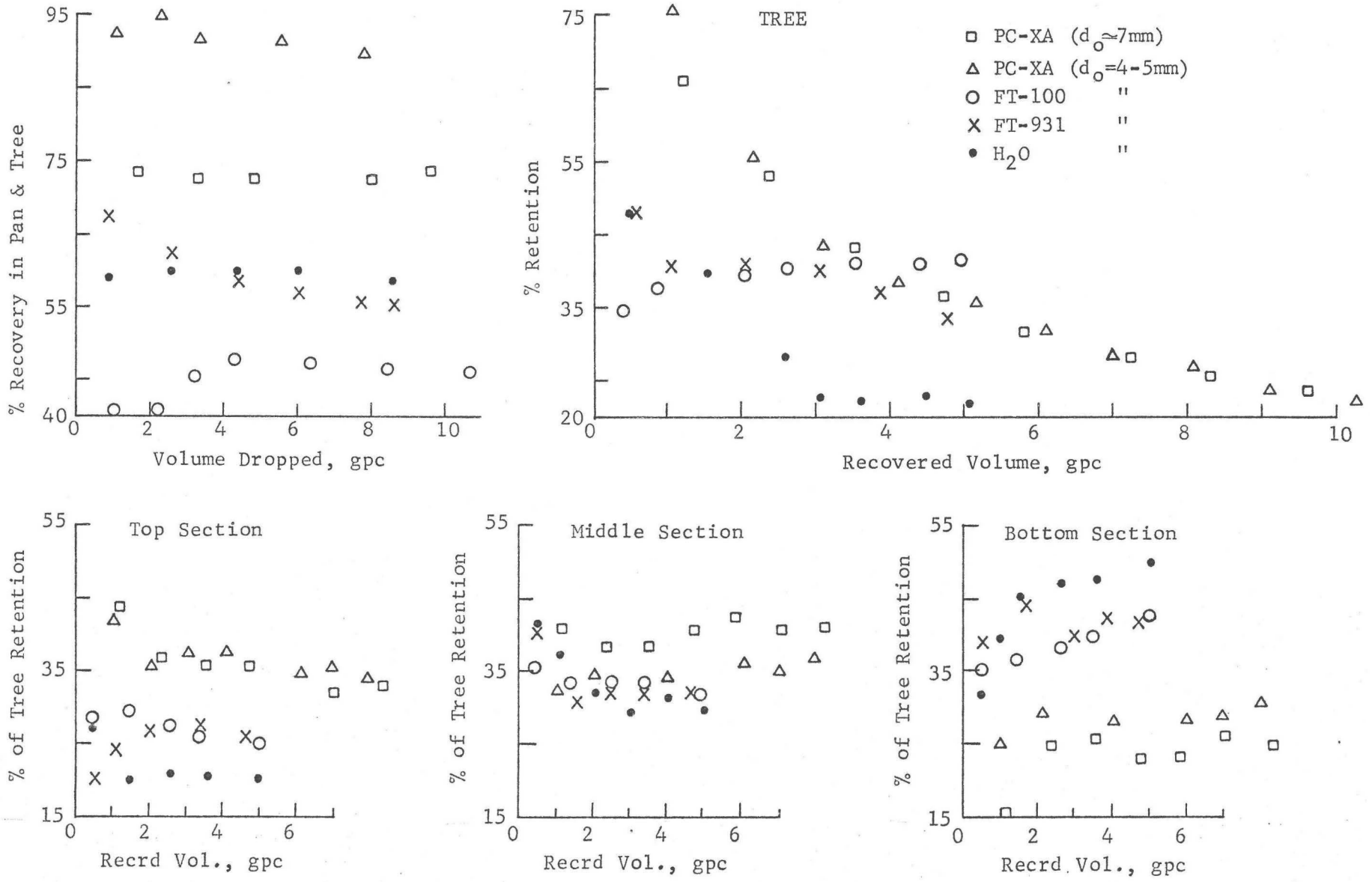


Figure 51. Experimental Retention of the Impacted Liquids on the Pine Needle Structures. The Fluids and Tree Sections are Not Directly Comparable Because the Surface Areas of the Trees and Their Sections are Not the Same.

tree and the pan. The relative ordering of the fluids is the same as found for the birch dowel tree (Figure 29), and is generally consistent with the previous findings. Figure 51 also shows the percentage of liquid retention of the fluids in the tree and its sections. However since the surface area of the different trees and their sections was probably somewhat different, it is not valid in principle to make a detailed comparison of the results for either the different fluids or tree sections. Nevertheless since the results were generally consistent with the observations made during the experiments, it would appear that the detailed surface area of the tree and its sections may be of secondary importance to the gross features and properties of the tree in retaining the liquid. Thus the results should have at least qualitative significance. Figure 51 shows that water was least retained of all the fluids in the top section of the tree, as well as the tree as a whole; whereas Phos-Chek XA (both drop sizes) was retained most in the top two sections of the tree, as well as the tree as a whole. The percentage retention of Fire-Trol 100 in the tree was essentially constant and independent of fluid volume, whereas the fraction retention of the other fluids decreased with increased volume.

Since the surface area of the fuel structures was not known, it was not possible to make an estimate of the average film thickness for the various fluids retained on the trees and their sections. However it is possible to use the fluid retention curves of Figure 51 (using Eq.3) to make plots of the product of the average film thickness and surface area vs recovered fluid volume, and these are shown in Figure 52. If it is assumed that the effective surface area of the various trees and their sections that retained the liquid were about the same, then these curves show the approximate relative differences between the film thickness of the fluids. It may be seen that Phos-Chek XA (both drop sizes) had the greatest thickness in the top two sections of the tree as well as the tree whole, and water had the smallest thickness. The two Fire-Trol fluids were roughly the same. Water had the greatest thickness in the bottom tree section, due to its great tendency for dripping from the needles in the upper sections. These results agree with the observations made during the wetting experiments.

5.4 WETTING CHARACTERISTICS OF A SMALL REAL FUEL STRUCTURE

As a culmination of the wetting studies on various kinds of model fuel structures, experiments were conducted on a real fuel structure. In order to accommodate the size and weight requirements necessary for the scale and dropping, small Juniper Tam (Juniperus sabina Tamarix) trees (shrubs) were used in these experiments. The trees were about 7.5 in. high and 8 in. wide, and were cut off near the ground at the primary stock just before a test. For the test, the tree was supported by inserting the bottom end of the primary stock into a hole drilled in the top end of a 2.5 in. long, 1 in. diam. aluminum rod. This rod was then supported by the rod attached to the Teflon base which was mounted on the scale. Figure 53 shows the trees used in the experiments.

5.4.1 Wetting Behavior, Liquid Recovery and Tree Retention

In order to provide a constant surface area for evaluating the wetting characteristics, an experiment was first conducted on a tree using

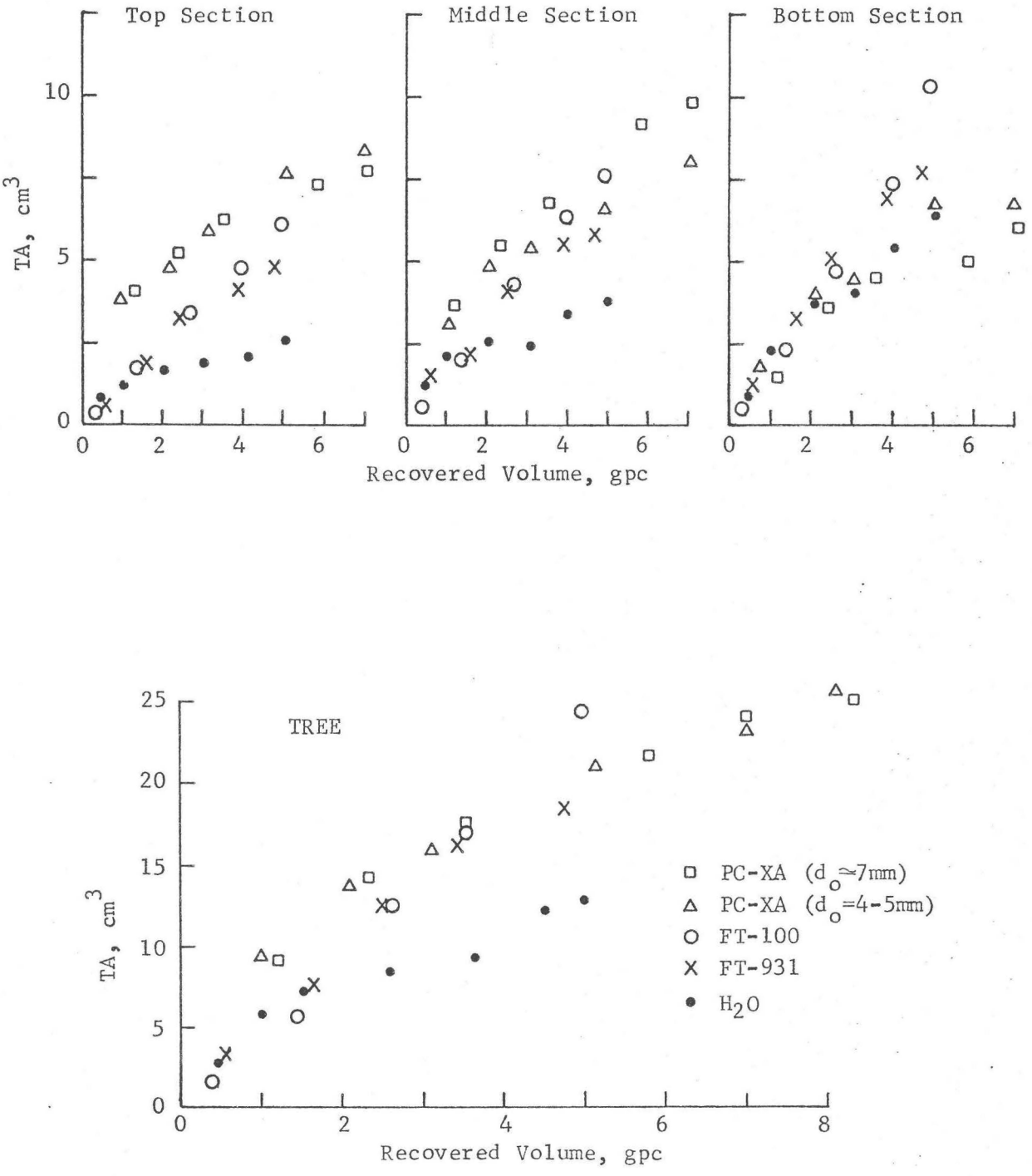
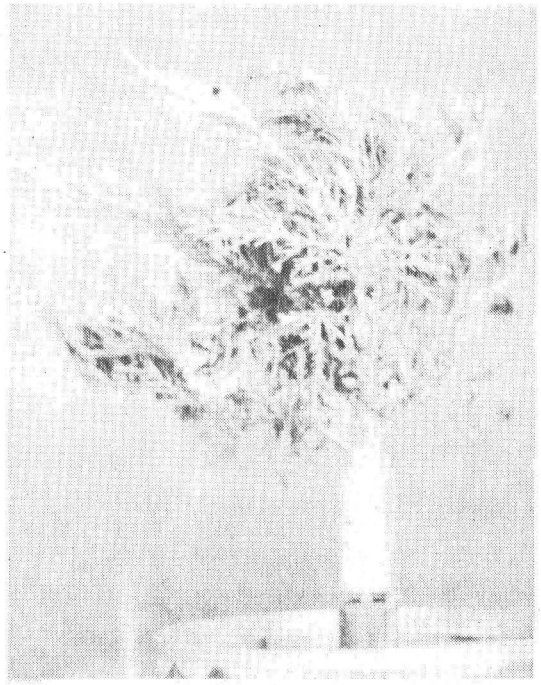
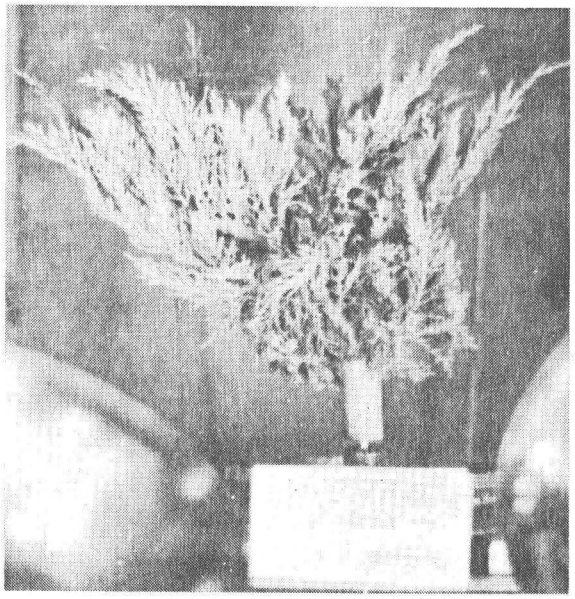


Figure 52. Product of Film Thickness and Surface Area of the Retained Liquid on the Pine Needle Structures.

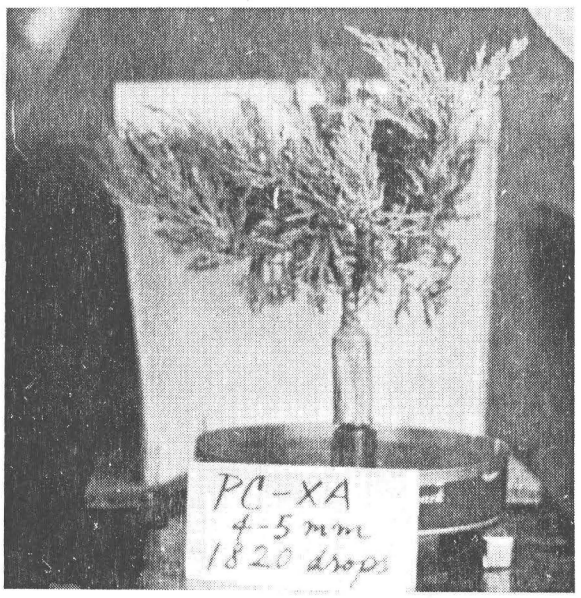
H_2O 5 gpc



FT-931 6 gpc



FT-100 9 gpc



PC-XA 9 gpc

Figure 53. General Appearance of the Juniper Tam Trees.

water. The tree was then dried to essentially its original weight, and the experiment was repeated using one of the retardants. A different tree was then used, first with water and then a retardant. In this manner the wetting characteristics of the three retardants was obtained relative to water at a constant surface area. The experiments were conducted using medium sized (4-5mm) drops of the retardants, and also large (7mm) drops of Phos-Chek XA.

The general wetting behavior of the tree, as observed during the experiments, was essentially the same as obtained with the previous fuel structures. The mechanism involved impact splatter, run and drip, with Phos-Chek XA giving the least splatter. Because of the compactness of the trees, most of the splatter of all the fluids was retained in the trees. For water, Fire-Trol 931 and Phos-Chek XA, limb run and drip, stem flow and needle drip was observed, with Phos-Chek XA undergoing the most extensive needle drip. Fire-Trol 100 underwent only limited limb drip and stem flow at high fluid volumes, and essentially no needle drip.

Figures 54 and 55 show the percentage recovery of the dropped liquid in the tree and drip pan. Phos-Chek XA (both drop sizes) was recovered most efficiently (as usual) followed by Fire-Trol 100, water and Fire-Trol 931 (in one case the latter two fluids were reversed). These figures also show the percentage of liquid retention in each of the four trees used in the experiments. In all cases the retention of the retardant was greater than that of water. For Phos-Chek XA, Fire-Trol 931 and water, the percentage of retention decreased sharply with increasing fluid volume, but for Fire-Trol 100 the retention was essentially constant (as usually found before) until large fluid volumes were dropped.

5.4.2 Relative Film Thickness

Since the retention of the three retardants were each measured with respect to water on a common fuel tree, it was possible to compute the relative average film thickness of the retardants with respect to water. Using Eq. (3), the quantity $TA = m/\rho_o$ was plotted as a function of recovered volume in gpc for each retardant and water experiment used with a common tree (the plots are not given here). Since the surface area of a tree is constant for each retardant/water experiment, the ratio of the film thickness of the retardant to that of water at any recovered fluid volume can then be obtained by division. The results of these calculations are summarized in Figure 56.

This figure provides direct evidence of the differences in the relative amounts of the various liquids that was retained in the tree. It shows that above about 1 gpc the average film thickness of Fire-Trol 100 was significantly greater than that of the other fluids, and increased with increasing fluid volume. At the lower fluid volumes the film thickness of Fire-Trol 931 was slightly greater than that of Phos-Chek XA (for equal drop size), but at the higher volumes the values were roughly equal and constant (independent of volume), due to drip. The large drop size of Phos-Chek XA gave a little larger film thickness than the medium size, and again attained a constant value at large fluid volumes. The film thickness of Fire-Trol 100,

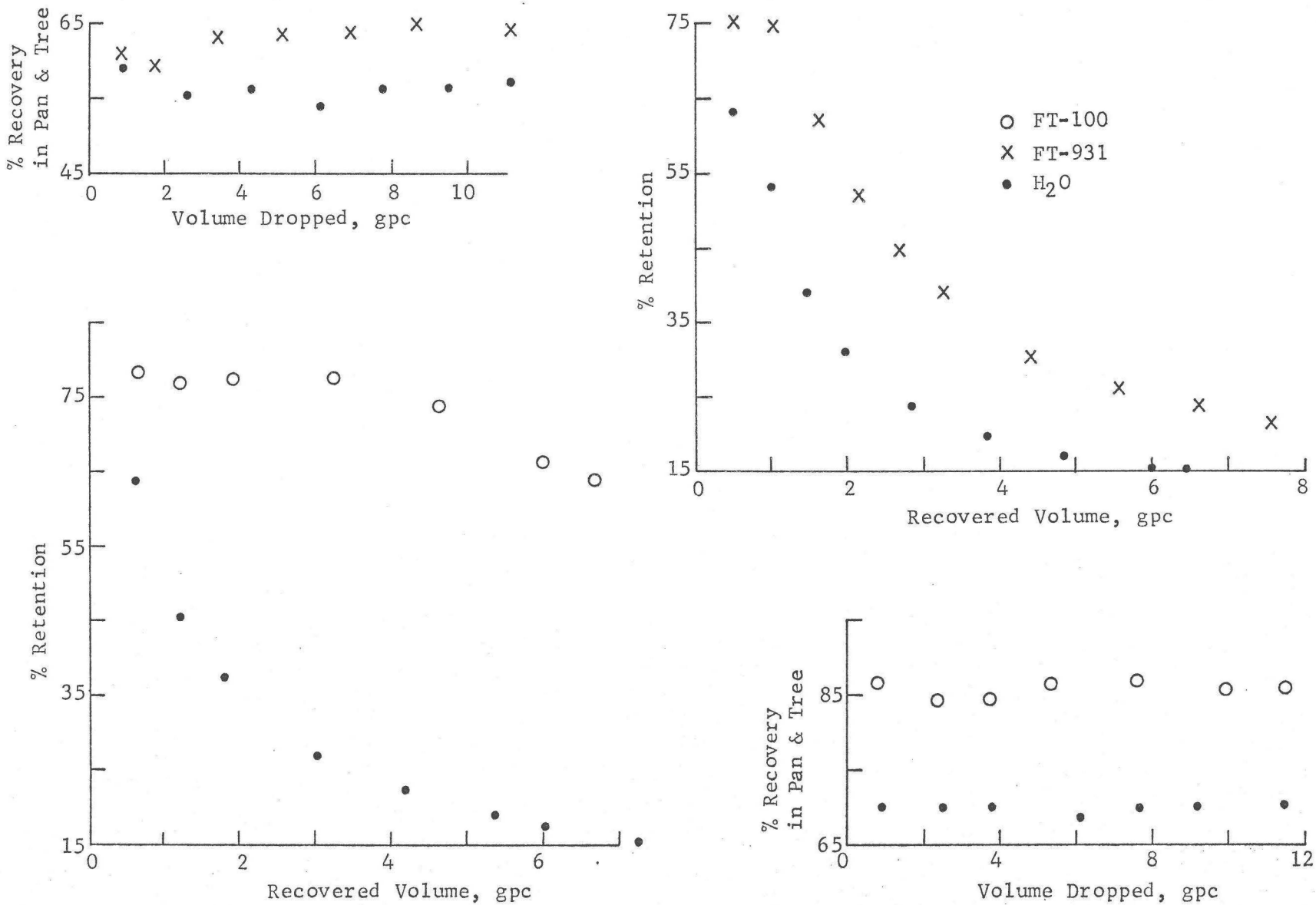


Figure 54. Experimental Retention of Impacted Water, Fire-Trol 931 and Fire-Trol 100 (4-5mm Drops) on Small Juniper Tam Trees.

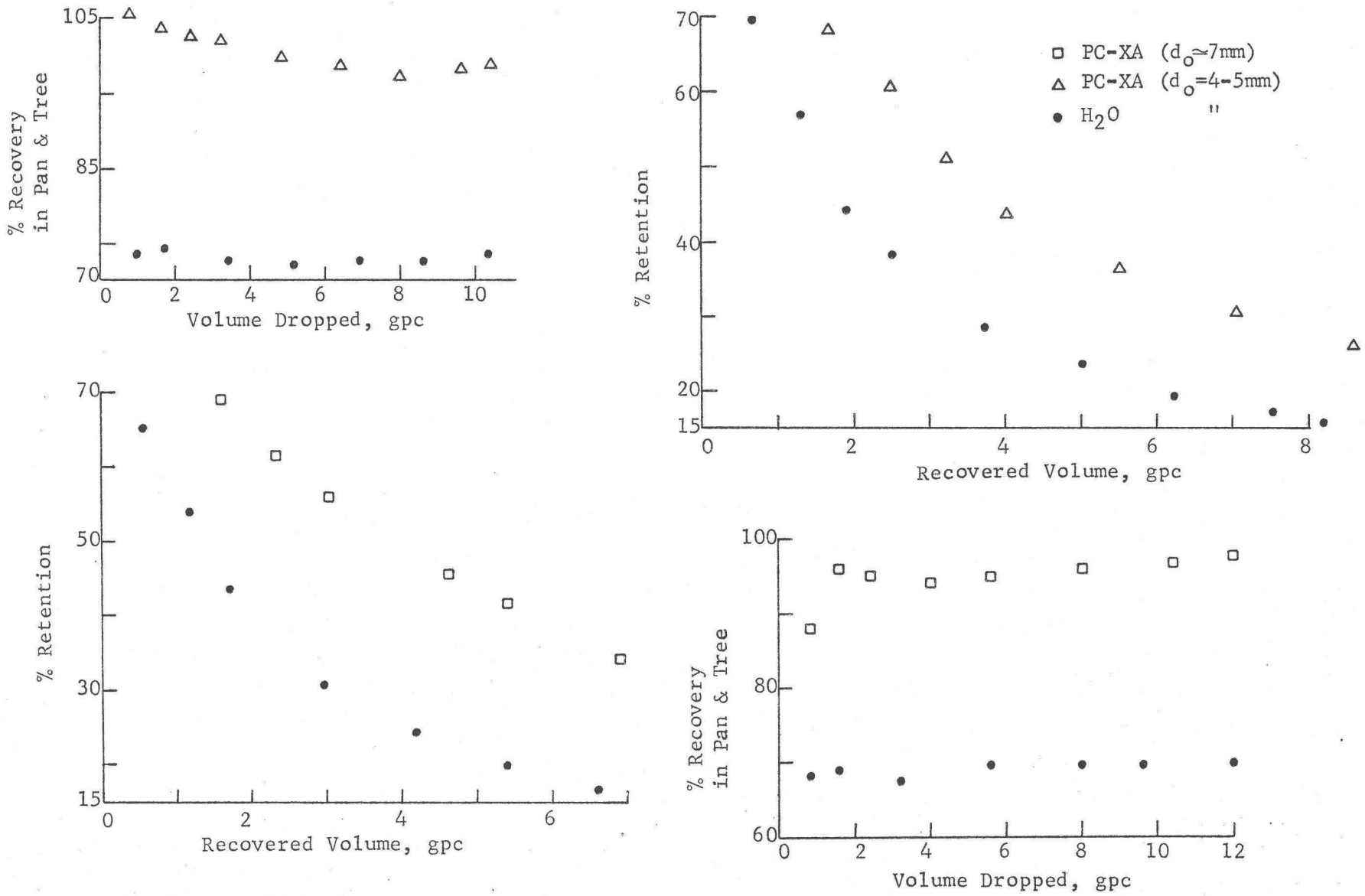


Figure 55. Experimental Retention of Impacted Water and Phos-Chek XA on Small Juniper Tam Trees.

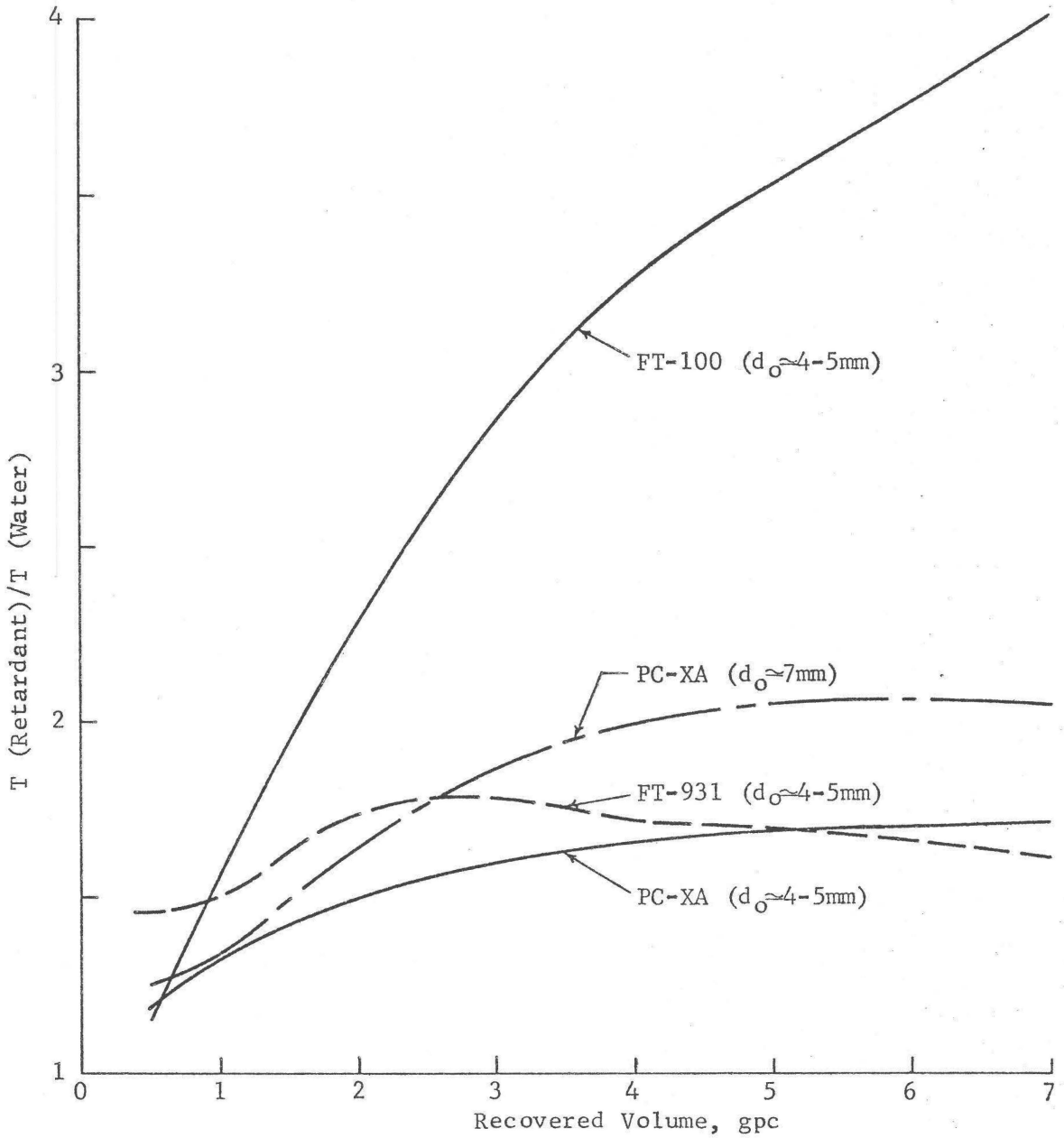


Figure 56. Measured Average Film Thickness Relative to that of Water on Small Juniper Tam Trees.

Fire-Trol 931 and Phos-Chek XA were all greater than that of water (the film thickness ratio is greater than unity).

The film thickness ratios given in the preceding figure for the Juniper Tam trees are greater than those measured on the birch dowel tree by dipping (Table VIII). In that case the relative film thickness of Fire-Trol 100, Fire-Trol 931 and Phos-Chek XA to water was 2.14, 1.21 and 1.14, respectively. The increased thickness for the Juniper Tam trees may be due to fuel composition and/or surface roughness effects.

6. FURTHER DISCUSSION AND ANALYSIS

It is well known that the wetting of a fuel by an aerial-delivered fire retardant rain involves the impaction and splattering of individual liquid drops on portions of the fuel, followed by run (i.e., liquid flow) and drip of the liquid over other portions of the fuel. The results of this investigation have provided various details regarding the manner in which these processes occur, and elucidated some of the factors that control the overall wetting of the fuel. They have also demonstrated that in general the wetting characteristics do not correlate directly with fluid properties. This indicates that in these cases either the surface properties of the fuel have a significant effect on the wetting process, or that two or more of the specific processes (splatter, run and drip) that contribute significantly to the overall wetting are affected in different ways by fluid rheology.

6.1 ON THE DEVELOPMENT OF A WETTING MODEL

One of the objectives of this program was to develop a simplified model that will characterize the effects of the important fuel and fluid parameters, including fluid rheology, on the wetting characteristics of a fuel, and contribute toward a later evaluation of the wetting of a defined fuel complex by a real aerial-delivered retardant cloud. This has presented some problem in view of the general complexity of the wetting event (non-correlatable results just mentioned, and fuel composition effects). Nevertheless preliminary studies have been conducted in which a general approach toward this goal has now been developed, but lack of time prevented its application to the present data. Moreover additional experimental information will be required in order to generalize the model for field application. A summary of these studies will now be given.

6.1.1 Stratum Fuel Wetting

The results of the dropping experiments showed that the droplet wetting of the model tree dowel structure occurred in a stratum (layered) manner. This may be seen in the many figures (Fig. 29-55), in which the liquid retention and average film thickness were plotted for the individual sections of the trees. In most (but not all) cases the liquid retention is greatest in the top layer and decreases in lower layers. The wetting of a fuel by a retardant rain is most usefully discussed using stratum concepts, since most real fuels are made up of branch layers in one form or another, which though not always identical, can nevertheless be defined grossly in terms of certain parameters.

For purposes of the present discussion an interesting concept given by Anderson of the Forest Service[15] will be utilized. The wetting of a fuel made up of various strata by a vertical rain of retardant was considered from the viewpoint of the attenuation of radiant energy by an absorbing medium. The following equation was obtained for the concentration, C_n of retardant transmitted through n number of fuel strata.

$$C_n = C_{n-1} \left[\exp(-afL) + F\right] \qquad (4)$$

where C_{n-1} is the fluid concentration above the stratum, n, and L is a stratum thickness. The exponential term in this equation accounts for liquid loss by interaction with the fuel, and F is the fraction of the interacting fluid that is not retained in the stratum. Thus F accounts for liquid that is lost from limbs or the stem (after droplet impact) by side splatter, run and drip. The term a is analagous to the absorption (or extinction) coefficient for radiant energy, and corresponds to the surface area (S) to volume (V) ratio of the stratum element of the fuel ($a = S/V$)(the total surface area of the stratum element can capture retardant; whereas only the frontal area blocks radiant energy). The term f is the packing ratio of the fuel, i.e., the ratio of stratum fuel volume (V) to total stratum volume (V_s), ($f = V/V_s$). It corresponds to the solute concentration term in the Beer law equation for absorption by the solute dissolved in a transparent solvent (fuel in air). It was shown in Ref. 15 that Eq.(4) could successfully account for the liquid loss in a vertical rack made up of dowels that was used by the Forest Service in field dissemination tests to study the vertical distribution of retardant in a fuel. No effect due to retardant rheology was found in these tests.

The concentration (C_r) of liquid retained by a stratum element of a fuel (corresponding to absorbed radiant energy) is given by $C_r = C_{n-1} - C_n$. The fractional recovery of the liquid in a stratum element of the fuel is then given by

$$\frac{C_r}{C_{n-1}} = 1 - F - \exp(-afL) \qquad (5)$$

6.1.2 Application and Improvement of the Model

The application of Eq.(5) to the experimental data given in this report for the various fluids and tree structures at various values of recovered fluid volume (gpc) would give information regarding the effect of fluid properties and fuel composition on the fluid loss factor F. Thus for the tree as a whole, C_r = (% R/100) x gpc and C_{n-1} = gpc*, where R denotes measured liquid retention in the tree. For a section (stratum) of a tree, C_r = (% TR/100)(% R/100) x gpc, where % TR denotes the percent of the total tree retention that was retained in a particular section of a tree, and was plotted in the various tree section figures.** The value of C_{n-1} in this case between the various sections can be calculated using the experimental curves for the various tree sections. The

---

* In calculations using the recovered fluid volume, gpc, it should be remembered that the tree gpc may be slightly lower than the gpc used in the figures, as discussed in section 4.2.1.

** For these calculations it would be desirable to replot all of the figures involving tree section directly in terms of % retention vs gpc, as was done for the tree as a whole. This would allow a rapid calculation of C_r directly from the equation, C_r = (% R_s/100) x gpc, where R_s is the liquid retention in a particular section at a specified gpc. In retrospect this would have been a more meaningful and useful manner of presenting that data than the given plots. However time limitations precluded the recalculating and replotting of the data in this manner, but it would make a very useful addition to the data presentation.

values of the exponential parameters in Eq.(5) are easily calculated for the model trees. Thus considering one section of a tree to be a stratum unit gives: $a = 10.95\ in^{-1}$, $f = 0.0562$ and $L = 2$ in.

Although Eq.(5) can be applied to the present data to obtain F under various conditions, it may be seen that what is really needed is a way to evaluate F in terms of the various parameters that control it. It would be expected that F would depend on the effective viscosity of the fluid, surface tension, fuel composition (and possibly roughness), and in some cases drop size. It would also be expected to depend on the magnitude of the recovered liquid (gpc), and the geometry and dimensions of the fuel, which can be characterized in terms of the product, afL.* However the analytical evaluation of F in terms of the fundamental processes that control it does not appear feasible at the present time. Nevertheless if experimental data of the type given in this report for the model trees were available over a sufficiently large range of variables, it would be possible to fit this data by empirical equations that could be used for predictive purposes.

In this case then, Eq.(5) could be applied directly toward estimating the wetting behavior of a real fuel complex by a retardant rain, as well as provide information which in conjunction with the results of Ref. 6 could be used to optimize the fluid rheology for both optimum drop characteristics and fuel wetting for various fuels. The necessary additional studies required to accomplish this will now be summarized.

6.1.3 Fuel Composition Characterization

The results of the studies indicated that the surface composition of the fuel has an effect on the liquid retention in some cases, and it is thus desirable to have some way in which to characterize the surface composition in the model. The characterization should also relate to the fluid properties, since the wetting consists of the bonding or adhesion of the fluid with the fuel surface. A potential way of doing this is by use of the surface energy, W_{ls}, at the liquid-fluid interface. This energy is a measure of the work required to separate the solid from the liquid, and is given by[16]

$$W_{ls} = \sigma(1 + \cos \theta) \qquad (6)$$

where σ is the conventional surface tension of the liquid, and θ is the contact angle of the liquid on the solid surface. Measurements of W_{ls} should be made for the retardants on typical fuels to establish the range of W_{ls}, and provide values for use in analyzing wetting in the field. One way of possibly doing this is by measurement of the contact angle of the fluid resting on the fuel surface. Another potential method is by the direct measurement of W_{ls} using a tensiometer, in a manner somewhat analogous to the measurement of the normal surface tension of a liquid.

---

* F will also vary with the stratum number.

6.1.4 Additional Wetting Experiments

In order to establish the functionality of F suitable for predictive purposes, some further model wetting experiments are needed. For example, the present studies provide only a single value of afL in Eq.(5), but three values would be needed to establish an extrapolatable curve. These experiments should be conducted with the same general type of model trees (dowel trees) used here, but designed to give other values of afL. The three sections of the tree should be identical, so that the liquid loss from the various strata occurs at constant afL. The experiments should again be conducted with the various retardants to provide different values of effective viscosity and surface tension. They should also be conducted with several different composition trees to provide a range in W_{ls}. The compositions should include some of those studied here, and be selected on the basis of the fuel characterization results. It should be noted that these experiments can be conducted much more rapidly than in the present studies, since it is now recognized that only about one-half of the weight measurements used in the present studies are required, and it would not be necessary to use splatter cards or take pictures, unless desired.

6.1.5 Model Correlations and Data Analysis

Subsequent to the preceding studies, the experimental data should be correlated using Eq. 5, and the correlations should also include the data in this report. This would entail some effort. The resulting values of F should then be examined parametrically with regard to the effect that the dominant fluid and fuel properties have on its value and parameter variation characteristics. The object would be to obtain an empirical expression for F in terms of its controlling parameters, based on the experimental data. Once this has been done, this expression could be used along with Eq. (5) to make field predictions. In this case then, the real fuel complex (e.g., a tree) could be broken into various stratum layers (with different values of afL), and the wetting characteristics calculated as a function of fuel volume using a computer.

The nature of the function F is not known, but for illustrative purposes consider that it may be put in the form

$$F_n = \frac{C_n}{\eta_e^b \, \sigma^c \, W_{ls}^d} \qquad (7)$$

where η_e is effective viscosity, σ is surface tension and W_{ls} is interfacial fuel surface energy. The value of the empirical parameter C_n is expected to depend on the fluid volume (gpc) and fuel description (afL). Likewise the parameters b, c and d may also depend on gpc and afL, but their variation is expected to be small. The value of F may also depend on drop size in some cases, and the drop size dependence could depend on the value of afL.

The best method of expressing F is not known, and must be determined from an analysis of the experimental data. This analysis can possibly be guided by standard modeling theory[17] in which the various parameters that control an event are arranged mathematically into unique dimensionless groups. For the present problem involving droplet impact, run and drip it would be expected that the Reynold's number, Re, Froude number, Fr, and Bond number, Bo, would be involved, i.e.,

$$Re = \rho v D/\eta \qquad (8)$$

$$Fr = V^2/gD \qquad (9)$$

$$Bo = g_1 D^2/\sigma \qquad (10)$$

where v is velocity, D is diameter (drop or fuel), g is gravitational acceleration, ρ is density and g_1 is fluid acceleration. There would also be other dimensionless groups that must be satisfied. The general form of the groups involved indicates that it would probably not be possible to use modeling theory by itself to extrapolate the results of model experiments up to field conditions. In order to do so it would be necessary to conduct the model experiments in a different manner than which they were conducted. For example, it would be necessary to model the drop size (as well as tree size) but use the actual (real) impact velocity of the drops that occur in the field. This is not possible however, since in the experiments the terminal impact velocity is largely controlled by the drop size. It would thus appear that the suggested approach based on Eq.(5) has much greater merit, and the application of this equation to real problems requires only an empirical (but valid) expression for F based on model experimental data.

7. CONCLUSIONS

The results of this investigation have provided many details regarding the wetting behavior of fuels by falling liquid drops, and demonstrated the complexity of some of the processes involved. They have also demonstrated that there can be significant differencesbetween the apparent effect of fluid properties on the retention of a liquid by a single dowel exposed to a single droplet impact, as opposed to a more complex fuel structure subjected to multiple impacts accompanied by liquid run and drip. Of particular interest for the present purposes is that the studies showed that the wetting efficiency of a fuel by droplet impaction generally does not correlate directly with fluid rheology, and that the surface composition of the fuel can have a significant effect on the liquid retention. Droplet size generally has secondary or negligible effect on the overall wetting, and its effect often relates to impact momentum effects in relation to fuel structure.

In bringing this long report to an end, it is useful to summarize here some of the important overall findings of the program, and the conclusions derived therefrom.

7.1 SUMMARY OF FLUID EFFECTS ON FUEL WETTING

7.1.1 Impact Splatter

The experiments using both single dowels and tree dowels showed that

the impact of a dowel by a liquid drop falling near terminal velocity (large drop height) produces a significant amount of side splatter, and simultaneously coats a portion of the dowel at the impact site with a film of liquid. For the liquids which have a low effective viscosity under high shear rate conditions (water, Fire-Trol 931 and Fire-Trol 100, Table III), the splatter is produced in the form of a large number of small drops and spray. For Phos-Chek XA, however, which possesses significant elasticity (large effective viscosity), the splatter is in the form of a very few relatively large drops. During the wetting (by falling drops) of the bare limbed birch and polyethylene dowel trees, the impact splatter wetted various areas of the tree such as adjacent limbs, the underside of limbs and the stock. In addition however, a significant amount was lost (ejected) exterior to the tree and drip pan (the amount lost in this manner by Phos-Chek XA was small). On the other hand most of the side splatter was retained in the trees that contained secondary branches (the pine needle structure and Juniper Tam), and little was lost exterior to the tree.*

7.1.2 Liquid Retention on Dowels

The fractional retention of a liquid drop by a dowel after impact depends on the symmetry of the impact; the retention is greatest for a central impact, and decreases as the impact becomes more off-axis. The liquid retention (and spread area) increases if the dowel is prewet by the retardant (simulating earlier droplet impact), or inclined at an angle other than normal incidence. The fractional retention of the liquid decreases with increase in drop size, but the absolute quantity of retained liquid increases because of the large drop size. The retention also increases with increase in dowel diameter (for constant drop size).

The high speed photographs showed that the impact of a drop with a dowel causes the liquid to initially undergo a flattening and spreading, followed by fracture of the liquid as it flows laterally off the sides of the dowel in the form of a sheet. For Phos-Chek XA the fracture occurs by a narrowing (necking) of the flowing fluid, which ultimately becomes a ligament near the end of the event.** This necking behavior results from the elastic nature of the flowing fluid. On the other hand, although the impact spreading in the initial phase for water, Fire-Trol 931 and Fire-Trol 100 is the same

---

* The impact of falling liquid drops with mobile fuel elements such as leaves, needles and grasses probably produces significantly less side splatter than the impact with a solid, fixed element such as a limb or stock. Moreover, the relatively large surface area of the mobile elements increases their chances of capturing splatter produced at adjacent elements.

** This behavior was also found earlier and discussed to some extent in Ref. 5.

as for Phos-Chek XA, it differs in the latter stages in that the sheet maintains essentially its full width during the flow process (it doesn't neck down) and then suddenly fractures along its entire width near the dowel. However the difference in the fracture properties (and fluid rheology) of the fluids at high impact velocities (large drop heights) apparently has little effect on the liquid retained on the dowel, since under these conditions the fractional retention of all the liquids is about the same.

In contrast, at low impact velocities (low drop height-simulating branch drip) fluid rheology does have an effect, and in this case Phos-Chek XA has a much higher retention on a dowel than the other fluids. The high speed photographs showed that in this case the fluid elasticity impedes (or prevents) fracture of the initially flowing liquid and pulls the liquid back on the dowel; whereas the other (non-elastic) liquids undergo fracture as before. The liquid retention on the dowel at low impact velocity is greater than at high velocity for all the liquids.

The single dowel studies also showed that the fuel surface properties can affect the liquid retained on the dowel after impact by a single liquid drop. A smooth polyethylene (PE) dowel was found to retain more liquid than a not-quite so smooth birch dowel. High speed photographs at low drop heights showed that for water and the two Fire-Trol fluids, the smooth surface of the PE dowel allowed the impacting liquid to undergo a partial wrap around of the dowel and expose a greater area of it to the liquid. This resulted in a greater retention of the liquid than on the birch dowel, where the rougher surface prevented the wrap around effect (the liquid flow was lateral to the dowel axis). The wrap around also resulted in impact splatter being ejected under the dowel, as well laterally from its sides; whereas for a birch dowel where there was no wrap around, only lateral splatter was produced. In the case of Phos-Chek XA, the wrap around effect was prevented by the elastic forces developed during the flowing of the fluid, and these forces increased the retention (at low drop heights) by pulling the flowing liquid back on the dowel. At large drop heights the retention of Phos-Chek XA (as well as the other fluids) on polyethylene is greater than on birch because of the greater longitudinal spreading of the impacting liquid.

7.1.3 Tree vs Single Dowel Wetting Behavior

The increased liquid retention after drop impact on a single PE dowel vs a birch dowel was not observed for the wetting of smooth PE and birch dowel trees, except with Fire-Trol 100. As discussed before, the impact of a liquid drop on a birch or PE dowel produces a splotch (liquid film) at the impact site, together with side splatter. The impact splotch on birch is stable. However (except for Fire-Trol 100) in the case of PE the splotch is not stable, and after a short time (depending on various factors) the spread liquid contracts into ligaments, streamers and small drops. For a single impact these liquid pieces then remain on the dowel, but in the dowel tree they rapidly grow due to secondary impact and liquid addition by run and splatter. Consequently, except for Fire-Trol 100 the liquid is not bound firmly in the tree, but gradually leaks off

in the form of run and drip. This effect is very pronounced for water, which rapidly attains a low average film thickness that remains constant as the volume of dropped film liquid increases (Figure 40). The tendency for run-off of the liquids from the PE tree decreases in the following order: water, Fire-Trol 931, Phos-Chek XA and Fire-Trol 100; and the average film thickness increases in this same order. The apparent viscosity of the fluids at low shear rate increases in the same order as does also the yield stress of the liquids (Table III). Thus it would appear that the retention of the liquids on a smooth, inert surface correlates both with the low shear rate viscosity and the yield stress of the fluids, i.e., high fluid viscosity and high yield stress increases the retention and average film thickness of the liquid on the tree (the effective shear rate may be sufficiently small that fluid elasticity is of no consequence).* Increasing the surface roughness of the tree had little effect, except to possibly increase the retention of Phos-Chek XA slightly (the results with Fire-Trol 100 for the roughed tree were consistent with test giving the lowest retention for it with the smooth tree).

For the birch dowel tree there was no direct correlation of either percent liquid retention or average film thickness with any of the physical or rheological properties of the retardant (Table III). Qualitatively the extent of the dripping of the fluids correlated with their surface tension, i.e., low surface tension gave large dripping, but this correlation did not show up in the retention curves. Fire-Trol 931 has the largest retention and film thickness on birch, and Fire-Trol 100 has the smallest. These results indicate that either the surface properties of the fuel (composition and/or roughness) have a significant effect on the wetting, or that two or more of the specific processes (splatter, run and drip) that contribute to the overall wetting are affected in different ways by fluid rheology. Surface roughness did not have a significant effect for the PE dowel tree, but this result does not necessarily apply to all fuels or roughness conditions. The retention of Fire-Trol 100 on the birch, PE and roughened PE dowel trees was about 40%, and independent of fluid volume. In these cases then the surface composition does not seem to affect the retention. However it is disturbing that the retention of Fire-Trol 100 in the top tree half of the extended birch tree (identical to the basic tree) increased significantly (almost doubled) above that in the basic tree for some unknown reason, although the other fluids in the basic and extended tree (top half) were consistent. On the other hand the retention of Phos-Chek XA, Fire-Trol 931 and water did differ in the birch and PE trees. This result together with the fact that the rheological properties of Fire-Trol 931 are intermediate those of the other fluids, whereas its retention and film thickness in the birch tree are largest, appears to indicate that the surface composition properties of the fuel (possibly in conjuction with the fluid rheological properties) are of special importance in the fuel wetting process. The fuel surface properties that are of importance are not known, but probably relate to the adhesion between the retardant and the fuel. Drop size had little effect on the wetting characteristics of the birch and PE dowel trees.

7.1.4 Liquid Retention in Real Fuel Structures

In the case of the real fuel structures, the percentage retention of Fire-Trol 100 on the green willow, rolled green ivy leaf and pine needle

---

* At low shear rates the effective viscosity of Fire-Trol 100 is large compared with that of Phos-Chek XA, see Fig. 6, Ref. 5.

tree dowels was roughly 40% and essentially independent of fluid volume. The percentage retention of the other fluids decreased with increasing volume. These results are consistent with the general behavior of the fluids on the birch and polyethylene tree dowels. The percentage retention of Fire-Trol 100 on Juniper Tam was about double that on the other fuel structures.

The liquids with largest retention and film thickness on the green willow dowel trees were Phos-Chek XA and Fire-Trol 931, except at very large fluid volumes when Fire-Trol 100 predominated. Water was smallest. For the wrapped green ivy leaf structure, water and Fire-Trol 931 had the largest film thickness, followed by Phos-Chek XA and Fire-Trol 100. These results in comparison with those of the polyethylene tree shows that polyethylene is a poor simulant for either a green leaf or green willow fuel. The results for these fuels as well as for the pine needle structure do not correlate in a direct manner with the rheological properties of the fluid, but again indicate that the surface properties (composition) of the fuel are of importance. For example water, Fire-Trol 931 and Phos-Chek XA all run readily off of vertical pine needles. However in so doing, Phos-Chek XA and Fire-Trol 931 leave a thicker film on the surface of the fuel.

In the case of the Juniper Tam tree, Fire-Trol 100 was retained most effectively, followed by Fire-Trol 931, Phos-Chek XA and then water. These results again do not correlate directly with fluid rheology, and indicate a fuel composition effect.

In closing this section it should be pointed out that in general the magnitude of the fluid retention and average film thickness of the different fuel structures with comparable surface areas did not differ widely (except for the polyethylene trees). Likewise, differences in fluid properties and drop size generally did not cause exceptionally large changes in fluid retention and film thickness except at very large fluid volumes. Thus it would appear that except in certain cases, the magnitude of the gain to be expected in the liquid retention by the fuel from small optimizing changes in the rheological properties of the retardant would be of the order of several tens of percent. This can be of some significance in various cases. However since small changes in retardant rheology can simultaneously cause relatively large changes in the drop characteristics (drop size) produced by the aerial dissemination of the retardant, it would seem that the drop characteristics should nearly always be of prime concern when selecting the rheological properties of a retardant for use in aerial dissemination. Of course in the general case it would be desirable to use the type and concentration of thickener that would simultaneously optimize both the drop characteristics and fuel retention of retardant, as discussed in section 2.2.2.2. However it is likely that this dual optimization cannot be attained unless the thickener can be independantly added to the retardant in the field, and its concentration (and maybe also compostion) adjusted according to the fuel type (present information is inadequate to make the thickener concentration selection except for drop size). The ability to control liquid surface tension independantly could also be desirable (again, not enough is known to make the selection), but may be impractical.

7.2 MODEL DEVELOPMENT

An examination of the experimental results of the program in terms of the present understanding of the wetting of a fuel by a liquid rain resulted in the development of an analytical approach which can ultimately be used to make predictions regarding the wetting behavior of a real fuel complex by a real retardant rain. This approach is based on stratum wetting concepts (Eq. 5), and uses the results of model fuel experiments such as conducted on the present program to evaluate the fluid loss factor in this equation in a general manner. However, the model requires additional experiments and analysis to bring it to completion.

8. RECOMMENDATIONS

As discussed before, the results of this investigation have provided a quantitative basis for potentially predicting the wetting out characteristics of a fuel complex in the field by a real retardant rain, but the model requires additional experiments and analysis to bring it to completion. The necessary additional work was summarized in section 6 of this report. It is recommended that these additional studies be conducted so that the model can be used to help solve field problems of importance to the Forest Service.

The model is based on defining a fuel complex in terms of its individual layers (strata), whose pertinent properties can be defined grossly in terms of certain known parameters. The sequential wetting of the various layers are then calculated as a function of fluid volume using Eq.(5). The evaluation of this equation requires a knowledge of the fluid loss factor. This factor can be evaluated in a generalized fashion from model experiments such as conducted on the present program, but additional experiments are required (as well as the application of the model to the present data). Information is also required regarding the characterization of the surface composition of the fuel used both in the model experiments and in the field.

Accordingly, it is recommended that the studies necessary to complete the wetting out model and test it for use be conducted. These studies include:

a). The development of techniques to characterize the effect of fuel surface composition on the adhesion between the fuel and a retardant with specified properties,

b). The inverted application of the model to the results of the present model wetting experiments, in order to obtain information regarding the fluid loss factor,

c). The conducting of additional model wetting experiments so that the fluid loss factor can be evaluated over a sufficiently large range of variables that control the wetting process, and

d). The parametric correlation and analysis of the computed data so as to obtain a simplified and generalized expression for the fluid loss factor that can be used with the basic stratum wetting equation (Eq. 5) for field type calculations.

A brief discussion of these recommended studies was given in section 6.

REFERENCES

1. C. W. George, A. D. Blakely and G. M. Johnson, "Forest Fire Retardant Research," Report INT-31, USDA Forest Service, Ogden, Utah, 1976.

2. C. W. George and A. D. Blakely, "An Evaluation of the Drop Characteristics and Ground Distribution Patterns of Forest Fire Retardants," USDA Forest Service Res. Paper INT-134, IFR Experiment Station, Ogden, Utah, March 1973.

3. C. W. George, "Fire Retardant Ground Distribution Patterns from the CL-215 Air Tanker," USDA Forest Service Res. Paper INT-165, IFRES, Ogden, Utah, May 1975.

4. W. H. Andersen, R. E. Brown, K. G. Kato and N. A. Louie, "Investigation of Rheological Properties of Aerial-Delivered Fire Retardant," Report 8990-04 (Final), to Northern Forest Fire Laboratory, U. S. Forest Service, June 1974.

5. W. H. Andersen, R. E. Brown, N. A. Louie, P. J. Blatz and J. A. Burchfield, Ibid, Extended Study, Report 8990-05 (Final), December 1974.

6. W. H. Andersen, R. E. Brown, N. A. Louie, K. G. Kato, J. A. Burchfield, J. D. Dalby and L. Zernow, "Correlation of Rheological Properties of Liquid Fire Retardant with Aerially-Delivered Performance," Report 8990-08 (Final) to U. S. Forest Service, Shock Hydrodynamics, August 1976.

7. D. H. Swanson, "High Altitude Retardant Drop Mechanization Study," Final Report, Vol. 1, to Northern Forest Fire Laboratory, Missoula, Montana, Honeywell, April 1973.

8. R. E. Leonard, "Mathematical Theory of Interception," Forest Hydrology, W. E. Sopper and H. W. Lull, Ed., Pergamon Press, 1967, pp. 131-136.

9. D. H. Swanson and T. H. Helvig, "Capture of Retardants in Vertical Fuels," Final Report, Vol. 2 to Northern Forest Fire Laboratory, Missoula, Honeywell, April 1973.

10. R. F. Grah and C. C. Wilson, J. Forestry 42, 890 (1944).

11. J. Stratta and W. Livingston, "Ablative Fluids in the Fire Environment," 73d Annual Meeting of the National Fire Protection Assocn, New York, May 13, 1969.

12. C. S. Grove, S. T. Grove and A. R. Aidun, Fire Research Abstracts and Reviews, 4, 54 (1962).

13. H. F. Johnstone, W. E. Winsche and L. W. Smith, Chem. Rev. 44, 353 (1949).

14. B. S. Grim and J. W. Barry, "A Canopy Penetration Model for Aerially Disseminated Insecticide Spray Released Above Coniferous Forests," DPG-FR-C625A, Sept. 1975.

15. H. E. Anderson, "Forest Fire Retardant: Transmission Through a Tree Crown," Research Paper INT-153, USDA Forest Service, 1974.

16. S. Glasstone, Textbook of Physical Chemistry, D. van Nostrand, 1946, pp. 481-484.

17. W. E. Baker, P. S. Westine and F. T. Dodge, Similarity Methods in Engineering Dynamics, Haydon Book Co., 1973.